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Crown Envelope Shape Measurements and Models

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This paper addresses tree crown envelope shape modeling from the perspective of optical passive remote sensing. The aims are 1) to review the specific requirements of crown shape models and ground measurement techniques in optical remote sensing, and 2) to present preliminary results from empirical, parametric crown shape and volume modeling of Scots pine and Norway spruce applicable in Finland. Results indicated that the basic dimensions (maximum radius, its height and crown length) of tree crowns were better predicted for pines, but the profile shape of the upper part of the crowns varied more than in spruce. Pine crowns were also slightly less concave than spruce crowns. No regularities were observed concerning the lower part of the crowns. The asymmetry of crowns increased as a function of tree age for both species, spruce crowns being more asymmetric than pine crowns. A comparison of measured crown volume with several simple geometrical crown shape envelopes showed that using a cone as a crown shape model for Scots pine and Norway spruce underestimates crown volume most severely. Other crown envelope shape models (e.g. ellipsoids) rendered crown volumes closer to the measured volume and did not differ considerably from each other.

Keywords crown profile, Scots pine, Norway spruce, reflectance model, remote sensing
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1 Introduction

Plant architecture has traditionally been both a taxonomic identification characteristic as well as a key factor in modeling the relationship between structure and function, i.e. analyzing ecophysiological responses of a plant to various environmental changes. The 3D distribution of plant organs controls most of the interactions between a plant and its environment (e.g. Godin and Sinoquet 2005) and thus, realistic characterizations of canopy architecture at various scales are needed for modeling forest physiological processes since it couples, for example, micrometeorology with remote sensing (Fournier et al. 1997). 3D modeling of the architecture of various plants species has gained thorough attention during the past decades, and various formalisms of plant components, geometry and topology have been proposed for use in different applications.

Plant architecture can be viewed from several perspectives by emphasizing different factors – a fact which has resulted in various definitions of plant architecture in the course of time. For scholars of phytoactinometry and optical remote sensing, Ross (1981) defined plant architecture as “a set of features delineating the shape, size, geometry and external structure of a plant”. Later, in a wider context, Godin (2000) suggested that plant architecture should be characterized so that information on three features is included: plant ’decomposition’ (description of the different plant components), geometry (description of the shapes and positions of components) and topology (description of the connections between the components). In general, the latter definition of plant architecture leads to more complex formalisms, whereas Ross’s definition involves more general geometric features. This already implies that in remote sensing modeling the relationship between structure and function is a matter of less relevance, and canopy is viewed as a medium of radiative transfer.

The importance of crown shape in biological processes (e.g. photosynthesis, stand growth, survival and competition) is acknowledged today. Yet often a rather unknown application for many modelers of plant architecture or allometry is the field of vegetation remote sensing, which can be viewed as an extension of radiative transfer studies related to the traditionally more studied photosynthesis process. The geometric properties of a plant stand and the biochemical properties of the plant components and underlying soil result in the spectral signature air- and satellite-borne instruments register when flying over the vegetated area. In other words, the forest canopy structure modifies the incoming solar spectrum and produces a new, reflected and transmitted spectrum, which can be decoded to obtain information about the canopy. Therefore, an understanding of how various plant or stand architectural features, such as stand density, leaf area index or crown shape and volume, influence the spectral signature (reflected solar radiation) are a key to reliable interpretation of remotely sensed data.

The application of many current crown shape models – such as the ones designed for ecophysiological studies – is often not possible in remote sensing applications due to the specific requirements imposed by the algorithms used both in theoretical and practical studies dealing with the interpretation of satellite data. Therefore, there remains a clear need in the remote sensing and radiative transfer modeling community for developing tree crown shape models which can readily be used also in large scale applications.

In this paper, we address crown envelope shape modeling from the perspective of optical, passive remote sensing and focus on trees growing in forests. The primary aims are 1) to discuss the specific requirements of crown allometry field measurement techniques and crown shape models needed in optical remote sensing, and 2) to present new results from empirical, parametric crown shape modeling of Scots pine and Norway spruce in Finland applicable for use in the interpretation of remotely sensed images.

2 Crown Shape Measurements and Models

2.1 Field Measurement Techniques

Tree crown representations (developed originally for purposes other than remote sensing) can be classified into two groups (e.g. see reviews by Godin 2000, Boudon 2004): global approaches that consider a plant as a whole and represent it as an envelope surrounding the crown volume, and modular approaches, where a tree is represented by smaller geometric units of its repeated, modular components. Simple crown shapes, such as cones, cylinders and ellipsoids, have been extensively used especially in studies on canopy radiation regime (e.g. Oker-Blom 1986, Welles and Norman 1991, Kuuluvainen 1991, Chen and Leblanc 1997, Gerard and North 1997, Nilson 1999, Mõttus et al. 2006).

In this paper, a tree crown is abstracted as the volume which comprises the phytoelements of a tree. Crown shape is defined as the set of basic characteristics defining the smooth surface forming the outer boundaries of this volume, the ‘crown envelope’. This corresponds to the ‘global’ approach of describing plant architecture referred to previously. It is, however, somewhat arbitrary and scale-dependent, since defining the outer boundaries of the volume can be done using several techniques and with various levels of detail. For a single tree, the main challenge is to separate which space is within a crown and which outside a crown. When comparing crown shapes of different trees of different species, possibly growing under diverse climatic conditions, an even greater challenge is to devise the appropriate ‘smooth surfaces’.

The most commonly used techniques reported in literature for quantifying crown form in the field can be divided roughly into two categories: 1) methods which rely on measuring the projection of a whole tree crown (in different directions) and 2) methods which are based on measuring the locations or dimensions of single phytoelements forming the crown. The first group of methods provides a more approximate approach, and the level of detail depends on the number of angles (i.e. projections) considered in the measurement procedure. The latter group of methods results in a highly detailed data set (coordinates of all components).

The most common strategy to start modeling crown shape is producing allometric equations for the basic dimensions of tree crowns: crown length and crown maximum radius from, for example, routine forest inventory data. Traditionally, these are the only crown dimensions which have been collected from most experimental plots. This information can already be used to apply simple envelope models such as ellipsoids, cones or cylinders.

The extent of a tree crown in any direction can be measured directly. For this, one needs to know the heights at which branches are attached to the stem, and the lengths and inclination angles of the branches. For full-grown forest trees, these measurements are usually carried out destructively (Biging and Wensel 1990, Cluzeau et al. 1994, Roeh and Maguire 1997, Hann 1999, Marshall et al. 2003, Groot 2004). The method gives a reliable estimate of crown shape if the inclination angle of branches is determined correctly: this angle, if measured on a felled tree has a systematic difference compared to a standing tree (Hann 1999). The projection of a standing tree can be measured also visually in arbitrarily many directions, though the most common are, due to technical limitations and application demands, the strictly horizontal and vertical directions. The first method to measure the vertical projection of tree crowns in a forest was a hand-held instrument equipped with a mirror allowing the observer to look towards the zenith and record whether the exact point is between crowns or beneath a single crown or subjected to shading by 0, 1, …, n crowns (the sighting tube, e.g. Sarvas 1953). This is a simple optical device, and therefore the ability of the operator to distinguish a gap or a small twig on a branch will naturally be slightly dependent on the height of the canopy, i.e. the vertical distance of the crown from the instrument. Nevertheless, the ‘resolution’ of the instrument is very close to a point. This method and its alterations were first used to draw the maximum cross-section area of tree crowns, but have also been used to map the spatial distribution of tree crowns as well as canopy cover (e.g. Korhonen et al. 2006, Rautiainen et al. 2005, Williams et al. 2003, Jennings et al. 1999).

The previous method can provide information on the maximum cross-section area, but not on the distance of the measured points from the ground i.e. the vertical distribution (heights) of the crown radii. Measuring crown shape in the horizontal direction has been attempted with methods based on measuring the angle between the outer profile of the crown and the tree trunk, and the distance from the measurer to the tree. Two methods, requiring different equipment but based on this same principle, are the Crown Window (Hussein et al. 2000) and the angle measurer (Rautiainen and Stenberg 2005). The Crown Window is a transparent window, divided into squares of equal size, which is mounted on a tripod at a given distance from a tree. The height of the tree is measured with, for example, a hypsometer. Crown radii and their heights can then be determined by calculating the number of the grid squares the crown occupies when looked at through the window, or if a more detailed data set is desired, the crown profile can be drawn on the window and later digitized. The angle measurer, on the other hand, is a simple T-shaped stick with angles of 1° marked on it. From the operating location, the heights of points (8–10) along the crown profile are measured and the crown radii at the points are determined from the angle between the tree trunk center and crown outmost point at that height. Knowing the distance from the person making the measurements to the points up in the crown can be calculated, and then finally the crown radius at that height is determined. For both the Crown Window and the angle measurer, the distance of the person making the measurements from the tree at breast height required typically a 15–30 m free line-of-sight, depending on the stand density and tree height. Both methods have demonstrated, with acceptable accuracy, their ability in estimating crown radii and the corresponding heights for pine, spruce and beech trees growing in forests. The methods have generally performed better than those based on photography in dense forest conditions, and they require less processing of the measured data before it is available for further analyses. The main theoretical problem related to these techniques is the under- or overestimation of maximum crown width when all the branches are not perpendicular to the axis of the measurement device. However, the relative errors of this 'misclassified orthogonal branch' are fairly small (Hussein et al. 2000), and when only crown shape models (and not, e.g. regression models for predicting crown width from breast height diameter) are developed, can even be neglected.

Crown shape has also been estimated based on the shadow a crown casts. For example, Oker-Blom and others (1991) measured projected crown areas and shapes by rapidly marking the shadow of Lodgepole pine and Engelmann spruce crowns with temporary stakes on the ground, and then calculated the area as the sum of trapezoids within the marked crown shadow outline and perpendicular to the crown axis. A similar technique was used by Giuliani and others (2000): light sensors were placed on the ground and the shadow cast by peach trees was monitored. Finally, they used tomography algorithms to calculate crown volume from the 2D crown projections obtained at several different times during the day. However, these techniques require a sunny day and relatively sparse stands with smooth ground-layer vegetation and no understory trees, and have therefore not gained wider interest in crown shape modeling.

Photography, both with ordinary and hemispherical images and followed by (binary) post-processing of the obtained images, is currently perhaps the most popular method for quantifying both the horizontal and vertical projections of tree crowns (e.g. Phattaralerphong and Sinoquet 2005, Menalled and Kelty 2001, Brown et al 2000, Fournier et al. 1997). This is mainly due to the low cost of high quality digital cameras, but also the wealth of data provided by the images. It is the only technique from this group of methods which can provide the 'exact' outer profile line of a crown – the other methods rely on 2, 3, …, n points to describe the line (or curve) between the crown base and top. The technical problems related to making the measurements are mainly related to the positioning of the camera in the field and controlling the measurement angles and distances, and weather conditions (e.g. wind) (Phattaralerphong and Sinoquet 2005), whereas in the post-processing of the images the isolation of the target crowns and merging crown images with calibration templates are crucial steps (Brown et al. 2000). The uniformity of the background of the target crown in the images plays a key role in how successful the isolation is, especially in dense forests. Photography has also been used as a method for reconstructing crown volume with various computer visualization techniques (e.g. Kutulakos and Seitz 2000, Laurentini 1999). The number of photographs (angles) the tree needs to be viewed from varies with crown size and asymmetry. To determine the exact shape of complex objects, one hundred photos may be required (Kutulakos and Seitz 2000). In research related to remote sensing and absorption of light by vegetation, a visually exact reconstruction of the finest details is usually not required and the demands are somewhat lower. For small trees, for example, Phattaralerphong and Sinoquet (2005) have reported that already eight photographs taken around mango, olive and hybrid walnut trees in the main horizontal directions provided satisfactory estimates when compared to the data provided by direct digitizing the whole tree.

Difficulties associated with the photographic method are both theoretical and practical. Theoretically, from the silhouettes captured by the camera, only the "visual hull" or the "photo hull" of the tree crown can be determined (Kutulakos and Seitz 2000). In principle, a visual hull determined from a photograph is the same as a visual hull determined by, e.g., the angle measurer. The main differences are due to spatial resolution (millions of pixels vs. about a dozen measured angles) and ignoring the voids in the crowns when the angle measurer is used. Neither of the hulls determines the crown structure uniquely as, for example, they do not take into account voids inside the canopy that are blocked from the view of the camera by foliage elements. However, if a more general species-specific crown outer shape is required, the knowledge of the shape of these hulls is clearly sufficient. From the practical viewpoint, it may prove difficult to obtain even a single good photograph of a tree crown in a natural forest without any objects between the target crown and the lens. Also, to determine the visual or photo hull of the shape, the background has to be clearly distinguishable from the crown or the exact illumination condition at the moment the photo was taken has to be known. This is a very limiting restriction since, inside a forest, the background consists of other crowns with almost identical optical properties and light conditions vary extremely in both space and time.

A completely opposite way to quantify canopy structure is the approach where the dimensions and locations of all components forming a crown are first measured, and the shape of the crown is then described on the basis of these measurements. These methods are 1) digitizing all components (e.g. Sinoquet and Rivet 1997, Sinoquet et al. 1997), 2) performing ground-based laser scanning (a new technique) or 3) making the more traditional biometric measurements of all components (e.g. Mõttus et al. 2006, Xiao et al. 2003, Kuuluvainen et al. 1988, Kellomäki and Oker-Blom 1983, Gary 1976). Biometric measurements typically include information on crown length, distances between successive whorls, lengths of whorls, branches and shoots, orientation of branches, shoots and leaves or needles, whereas digitized and laser data can include all structural properties of the canopy if the data collection is done at a high resolution. Digitizing entire trees in order to obtain a model for the crown envelope is feasible only if the trees are relatively small and host a fairly small amount of modular parts (i.e. leaves, shoots). However, even then, an extensive data set of hundreds of trees is unattainable. In biometric measurements also the biomass of the components is often recorded – this information is not obtained with the two other groups of methods.

Finally, in addition to the outer profile, inner crown profile is also very important, though even harder to quantify due to all the visual obstructions. It is generally assumed that rather large volumes can be 'empty' of phytoelements close to the tree trunk, especially in shade intolerant species (e.g. Scots pine). Equations to characterize the inner profile have hardly been reported, though an example was presented by Baldwin and Peterson (1997) for nonjuvenile Loblolly pines, where they felled 86 trees and measured crown dimensions afterwards. In the crown shape model, they assumed symmetrical vertical cross-sectional profiles and used regression equations to describe the inner profile taper which was, for the study species, very close to a conical shape.

2.2 Crown Shape Models in Remote Sensing

Crown shape plays a dual role in the remote sensing literature. In practical applications, it is mainly used to acquire information on stand structure needed for forest management purposes. In combination with spectral information, structural patterns can be used in image interpretation algorithms (either physically-based or empirical) for species recognition. On the other hand, it also has a more scientific role in understanding biogeochemical processes of ecosystems as, for example, the key link between ecosystem structure, absorbed radiation and primary production. Only global crown envelope shape modeling approaches which are more easily applicable in various remote sensing models will be discussed in this paper.

According to the definition given in Section 2.1, crown shape is provided by the smooth surface of the crown envelope. To construct a model, we need to approximate this surface computationally efficiently, simply, and with sufficient accuracy. While computational efficiency and accuracy can be considered technical characteristics determined by the mathematical, electronical, and optical apparatuses involved in solving the given remote sensing problem, simplicity is essential to make the processes easier to understand and interpret for the researcher. Purely empirical approaches can also be used by evaluating interaction of radiation with phytoelements on a three-dimensional grid with varying optical properties determined by crown structure. However, models of this type lack the power of generalization and are more extensive computationally, if calculations are to be carried out on a large scale. If we have a geometric shape, a visual or photo hull of the crown to start with, we can construct a model by approximating this hull with some mathematical function. By changing the resolution at which the hull is calculated, we can eliminate unnecessary details and make the model applicable to a large number of individual crowns. A similar approach can be used if the locations of canopy elements are known. In this case, the crown shape function must be chosen such that a large fraction of phytoelements would be found inside the crown envelope if applied to an individual crown.

Remote sensing applications make use of the abstract division of foliage into tree crowns by dividing the path a photon travels inside the canopy into segments inside and outside crown envelopes. Inside a crown, different algorithms can be applied to calculate the fate of a photon, depending on the level of detail of the description of crown architecture. In the simplest case, crowns are assumed to be uniformly filled with foliage. In some models, higher level structure (whorls, branches) is also taken into account (e.g., Chen and Leblanc 1997, Peddle et al. 2004). Outside the crowns, photons travel without interactions. If all levels of canopy architectural detail for all tree species were to be included directly, the simulation of radiative transfer in a forest stand, when generalized over a large area in remote sensing applications (i.e. satellite images or image mosaics), would become unnecessarily complicated and computationally demanding. Therefore, a generalized (i.e. coarse) crown shape model which is based on empirical justifications (e.g. species specific shape parameters) and is empirically justified could be considered the most desirable for remote sensing studies.

To make the best use of such a simplified picture of canopy structure, it is most convenient to assume that crowns are convex. In this case, a straight line that describes the trajectory of a photon between two interactions intersects with the surface of a crown not more than twice: first entering and then (if it has not interacted) leaving the crown. This eases the calculations and is not in contradiction with the crown shape definition used in this paper. Although some empty (or sparsely filled) space may be introduced into the crown by using a convex envelope, this can be taken into account in the parameterization of the crown inner structure. Another common approximation is axial symmetry, reducing the 3D shape into a 2D curve rotated around the vertical axis.

Crown shape at any azimuth varies according to several factors that can be summarized as competition influences (e.g., proximity, location, and height of neighboring trees), and the shape is seldom symmetrical (Baldwin and Peterson 1997). Asymmetric crown models have been used in studies aimed at estimation canopy transmission and absorption (e.g., Brunner 1998, Groot 2004, Piboule et al. 2005), and even in canopy radiative transfer models (e.g., Cescatti 1997). However, they have not been used for remote sensing purposes. There are three main reasons for this: 1) there are hardly any data available on the asymmetry of actual tree crowns; 2) there have been no studies reporting that the asymmetry of tree crowns has a considerable effect on canopy reflectance; and 3) as the inversion of the radiative transfer problem is already an ill-posed problem, the possibility of retrieving additional parameters on crown asymmetry is very small.

The crown shapes commonly used in geometric-optical radiative transfer models are all axially symmetrical and convex. The most common shape used approximate a tree crown as an ellipsoid of rotation, or, equivalently, a sphere which can be changed into an ellipsoid by a simple coordinate transformation (e.g., Welles and Norman 1991, Nilson and Peterson 1991, Li and Strahler 1992, Li et al. 1995, Kuusk and Nilson 2000, García-Haro and Sommer 2002, Gerard and North 1997, Gerard 2003). A second popular option is a combination of a cone on top of a cyliner (e.g., Nilson and Peterson 1991, Chen and Leblanc 1997, Kuusk and Nilson 2000). By setting the height of the cylindrical part to zero, the tree crown will be approximated by a cone (Li and Strahler 1985). Although this might be feasible for a coniferous forest, it is generally considered to underestimate crown volume if crown height and diameter are taken directly from measurements.

In addition to radiative transfer models, crown shape is also needed in several practical forestry applications in optical remote sensing. For example, crown typology, defined jointly by crown size, color, status, contour, foliage cover and texture, is used in the identification of tree species in large-scale aerial photographs (e.g. Trichon 2001). In the interpretation of high resolution images, canopy allometry can also be used to directly detect properties of the stems once empirical relationships have been established (e.g. Kalliovirta and Tokola 2005, Korpela 2004, Anttila 2005) or to form crown shape templates or other approaches for locating e.g. tree top positions (e.g. Straub 2003, Sheng et al. 2001, Pollock 1998, Larsen 1997). Crown shape may, in the future, even more so become a key factor in distinguishing tree species from high-resolution remote sensing data. For example, in laser scanning applications which are currently under development, a crown shape parameter may have potential to be the main requirement for separating tree species from each other (e.g. Koetz et al. 2006, Sun and Ranson 2000).

However, it must be kept in mind that interpreting canopy architectural properties from remotely sensed images is not trivial. It may be difficult to detect, for example, the maximum radii of trees due to their close proximity (e.g. Kalliovirta and Tokola 2005) or, especially in the case of conifers, the strong noise from the background (understory) of the typically relatively sparse canopies may result in unreliable crown shape estimation even if multiangular reflectance data is used (Goel et al. 1997). Different spatial resolutions of the images may also provide problems for the interpretation techniques: when a set of images with different resolutions is used for crown size detection, having an a priori reference estimate of stand age may be needed selecting the optimal spatial resolution for a given geographical location (Song and Woodcock 2003).

Another perspective to crown shape modeling is reliable estimates of canopy volume. Relatively correctly approximated crown volume is especially important in forest reflectance modeling, since it defines the scattering medium and provides the boundaries for integration. The use of different crown shape models to characterize a tree naturally results in very different crown volumes (e.g. Boudon 2004, Nelson 1997). Moreover, in a theoretical simulation study, it was shown that crown shape and volume considerably influence the reflected signal – at equal tree density, canopy cover and LAI, stand reflectance was smaller in the case of conical crowns than for ellipsoidal crowns which have a larger volume (Rautiainen et al. 2004). Therefore, crown shape models need not only be correct for the top of the crowns (i.e. the part most visible to the human eye from above), but also produce a realistic volume.

3 Crown Shape and Volume of Scots Pine and Norway Spruce

3.1 Aim

The aim of the case study presented here as a part of our review was to examine the crown shape (outer shell enveloping the green biomass) of the two dominating coniferous species in Finland, Scots pine (*Pinus sylvestris* L.) and Norway spruce (*Picea abies* (L.) Karst) from the perspective of crown shape parameterizations used in radiative transfer models. The questions to be investigated were 1) how to measure quickly but reliably the shape and volume of pine and spruce crowns in a forest, and 2) how to parameterize the shape and volume of these trees. The main criterion set for the crown shape model was that it needs to be mathematically simple. The model could either be generalized for a given species or predicted for each tree individually from routine stand inventory data. In addition, crown volume and bidirectional gap probabilities (between crowns) should be easy to calculate. The specific objectives for the study were outlined as follows: 1) to investigate how the crown shape and volume of the study species differ, 2) to assess the general horizontal asymmetry of the crowns, and finally, 3) to produce a simple parameterization to describe the convexity of the crowns.

3.2 Materials and Methods

The vertical crown profiles of 250 Scots pines and 180 Norway spruces were measured in Suonenjoki, central Finland during June and July 2005. The profile line was defined according to the tips of living (green) branches. The site types of the study stands were restricted to monospecific and relatively even-aged, managed heaths. 25 pine stands and 18 spruce stands were chosen based on previous stand inventory data from the study area so that the stands represented a range of size classes from young to mature (Table 1). Ten trees closest to the stand (i.e. plot) center point were selected as study trees. After this, four profiles per tree (north, east, south, west) with eight to ten points per profile were measured using the angle measurer technique described in Section 2.1 (Field measurement techniques) and also in Rautiainen and Stenberg (2005). In other words, for each tree crown, the locations of eight to ten points (depending on visibility and crown length) along the profile line were measured, with the height and the crown radius at each point recorded. The first point measured was the base of the live crown and the last the crown top (i.e. tree height). Crown base was defined as the lowest branch above which there were at least two consecutive living branches. The points were placed on the crown profile as evenly as visual judgment in the conditions allowed and, also, to trace the main 'turns' in the crown profile curve. In addition, stand density and the breast height diameter of all the study trees were recorded.

Table 1. Summary of trees used in the case study.

	Scots pine	Norway spruce
DBH, cm		
Min	5.1	5
Max	48.1	35.2
Mean	17.6	19.2
Tree height, m		
Min	4.4	4.2
Max	31.5	26.7
Mean	15.3	16.4

A crown shape model was constructed to examine the convexity of tree crowns. In this study, we decided to test the use of a simple parameterization for crown envelope shape which is also suited for use in physically-based reflectance models. In other words, a crown envelope parameterization used together with forest reflectance models should have a high power of generalization and be computationally efficient (so that calculations can be made over extensive areas fast). Specific criteria for choosing the superquadric model was that input needed for it are fairly quick to measure as ground reference in Finnish forests, it allows both axial symmetry and asymmetry, and is computationally relatively light. The analysis was restricted to the upper part of the crown (i.e. the part above the maximum crown radius), since this is the part most visible to air- or satellite-borne remote sensors, and thus controls the geometric appearance (and the surface area available for escape of exiting photons) of the canopy in the upper hemisphere. On the other hand, the lower parts of the crowns were highly irregular in shape (due to low needle area density), and fitting a general curve was not possible.

An average crown profile of the four measured profile lines was used to fit a superquadric curve, also known as a Lamé family curve, to the upper part of each crown. In the chosen family of curves, a shape parameter (the exponent (t)) determines the convexity or concavity of the curve. The fitted curve was:

$$\frac{R_i^t}{R_{\max}^t} + \frac{h_i^t}{c^t} = 1 \tag{1}$$

Table 2. A summary of linear regression equations to predict the basic dimensions of crowns. DBH = breast height diameter (cm), H = height (dm).

Dependent variable	Scots pine	Norway spruce
Crown length (dm)	$= 26.53 + 0.26$ DBH, $r^2 = 0.75$	$= 26.86 + 0.52$ DBH, $r^2 = 0.83$
Crown max radius (dm)	$= 4.76 + 0.06$ DBH, $r^2 = 0.79$	$= 6.63 + 0.06$ DBH, $r^2 = 0.73$
	$= 7.00 + 0.10$ DBH $- 0.06$ H, $r^2 = 0.83$	$= 7.96 + 0.09$ DBH $- 0.05$ H, $r^2 = 0.77$
Height of crown	$= -17.41 + 0.80$ H, $r^2 = 0.94$	$= -21.71 + 0.69$H, $r^2 = 0.76$
max radius (dm)	$= -23.10 + 1.01$ H $- 0.15$ DBH, $r^2 = 0.95$	$= -22.73 + 0.98$ H $- 0.25$ DBH, $r^2 = 0.79$

where R_i is the crown radius (above R_{max}), R_{max} the maximum crown radius, h_i the length of crown above R_{max}, and c the total length of crown above R_{max} (i.e. distance between tree top and the height of R_{max}). The shape parameter (t) was obtained as a result of a least-squares optimization with the lowest point fixed at crown maximum radius and the highest point at the crown top. When t approaches 0, the shape becomes more cross-like, and when t approaches infinity, the shape becomes more rectangular. When t is 1 the shape is conical and when t is 2, the shape is ellipsoidal. The fitting was done iteratively pointwise and the tree-specific t was then obtained as an average of the pointwise t values. The number of points used for the fitting varied, since the relative height of maximum crown radii varied in the measured trees. Thus, when on the crown profile the maximum crown radius and the top of the tree were consecutive measured points, the exponent t was forced to be 1.

Simple linear regressions with tree height and breast height diameter (DBH) were used as independent variables to predict the basic dimensions of crowns. The statistical tests were performed with the SPSS statistical package. Next, crown volume for all study trees was calculated in five different ways: 1) as a sum of the measured frustums, 2) assuming the crowns were ellipsoids, 3) assuming the crowns were cones, 4) assuming the crowns were cylinders below their maximum radius and cones above it, and 5) assuming crowns were cylinders below their maximum radius and had an upper part determined by superquadric curves with the measured, tree-specific t parameter. The maximum radii and crown lengths for the trees were predicted using the simple linear regressions produced in this study (Table 2). The volumes calculated using the approximated shapes (i.e. methods 2–5) were then compared to the measured volume (method 1) to evaluate the usefulness of the different approximations. Finally, radial symmetry of tree crowns was assessed by dividing the crowns into four vertical parts: northern, eastern, southern and western quarters.

3.3 Results

To begin with, we will examine the basic dimensions of the crowns. These basic dimensions of crowns – crown length, maximum radius and its height– are the minimum information needed for simple geometric crown shape models such as ellipsoids, cones or cylinders. For both pine and spruce, crown length, maximum radius and its height depended relatively strongly on DBH and tree height (Table 2; Ervasti 2006). The dependence of the height of maximum crown radius on DBH and height was considerably greater for pine than for spruce. This may be partly due to the fact that spruce crowns are longer and the lower branches die more slowly than in pine. Generally speaking, the basic dimensions of pines had a slightly stronger dependence on DBH and height than the dimensions of spruce crowns. Including stand density in the regression equations did not improve the prediction results (data not shown).

Results from fitting the superquadric curves indicated that pine crowns are slightly more conical than spruce crowns: the average t in pines was smaller than in spruces (Table 3). However, the range of t values obtained for spruce was larger, suggesting in turn that the shape of the crowns is more irregular than in pine. A tight relationship of t with routine stand inventory data would be a clear advantage in predicting crown shape. Unfortunately, the shape parameter did not depend on any of the routine stand inventory variables, and it was not possible to form any regression models (Fig. 1). Linear regression models with several independent variables were also tested with this data set (Ervasti 2006), but the performance of the regressions in predicting *t* remained poor. Thus, based on this study, only a species-specific (i.e. average) *t* value is realistic and available for forming future crown shape models.

The relationship between crown volume and DBH was tighter for spruce than for pine (Fig. 2). A comparison of measured crown volume (i.e. the volume computed as a sum of the measured frustums) with several typical crown shape envelopes (cone, ellipsoid and cone + cylinder) (Fig. 3) showed that using a cone as a crown shape model

Table 3. Convexity of the upper part of tree crowns: the shape parameter *t*.

t	Scots pine	Norway spruce
Average	1.35	1.42
Stand. dev.	0.24	0.26
Min	0.79	0.91
Max	2.37	2.45
RMSE	0.85	0.86

for Scots pine and Norway spruce underestimates crown volume most severely. The two other crown shape models rendered crown volumes closer to the measured volume and did not differ considerably from each other. This suggests that, from the perspective of crown volume modeling, there

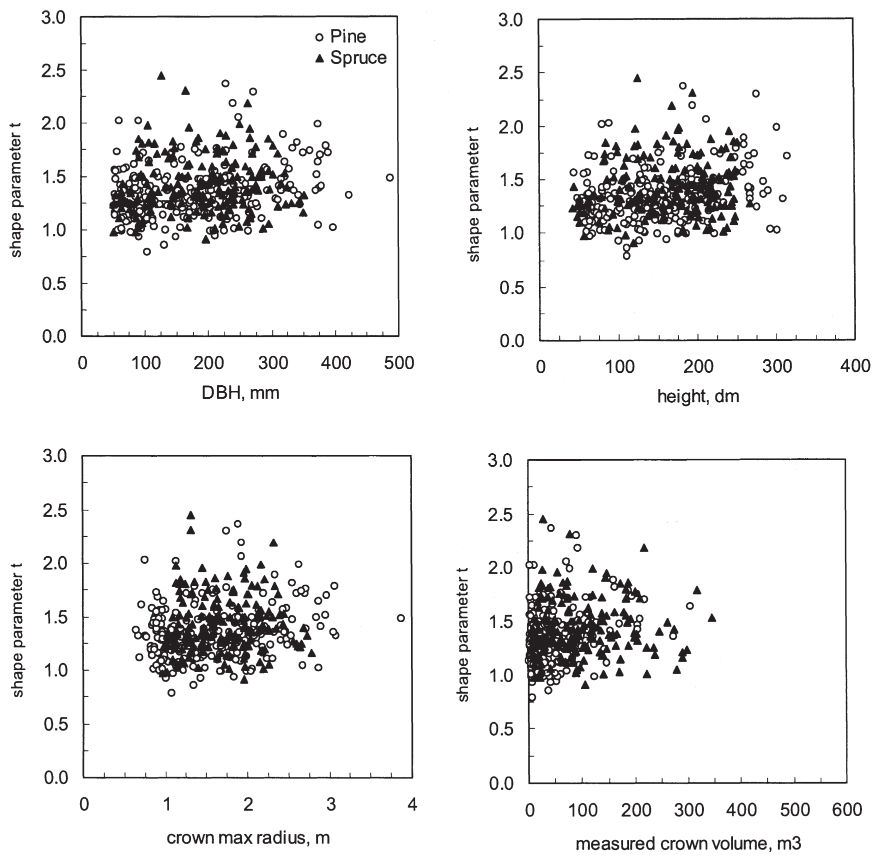


Fig. 1. The relationship of shape parameter *t* (Eq. 1) with crown dimensions of single trees for Scots pines and Norway spruces.

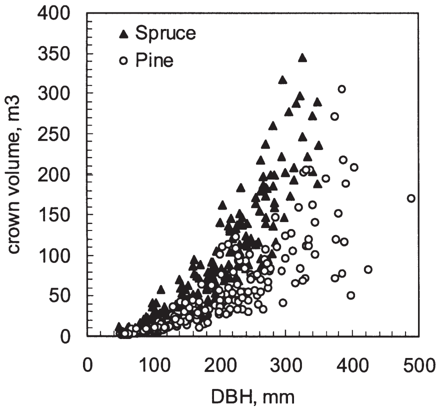


Fig. 2. A comparison of measured crown volume of Scots pines and Norway spruces.

is no additional advantage gained from carefully modeling the top part of a crown with a shape parameter (e.g. t) – an ellipsoidal crown shape model which requires only crown length and maximum radius as its input performs equally well for both species.

The general radial symmetry of crowns was the next characteristic to assess. So far, there have been no representative measurements of directional effects in forest grown pine and spruce crowns in Finland, but for example, based on common traditional belief, branches pointing towards south have been claimed to be longer than branches pointing towards north. To evaluate general directional effects, the study trees were divided into four DBH classes (<10 cm, 10–20

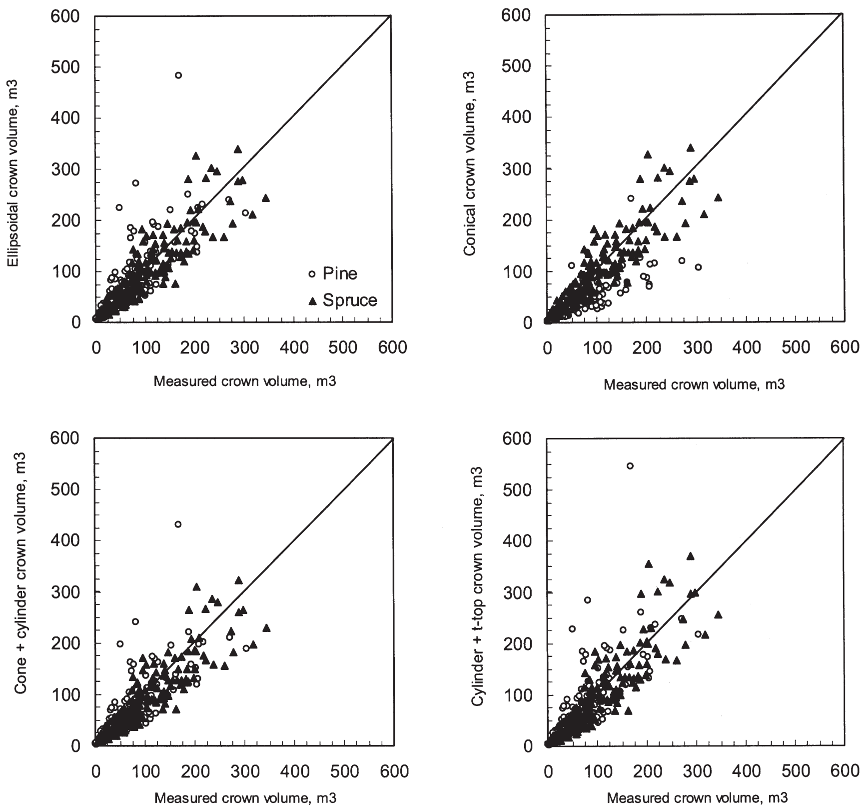
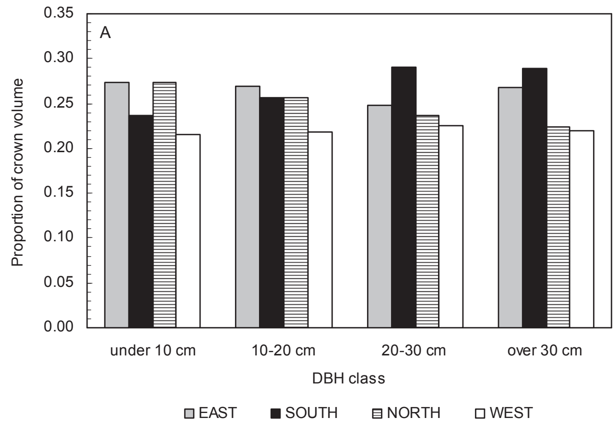


Fig. 3. A comparison of measured crown volume with computed crown volume. A. Crowns modeled as ellipsoids (RMSE: pine 16.4 m^3, spruce 22.4 m^3). B. Crowns modeled as cones (RMSE: pine 21.0 m^3, spruce 48.1 m^3). C. Crown upper part modeled as a cone, lower part as a cylinder (RMSE: pine 14.6 m^3, spruce 22.6 m^3). D. Crown upper part modeled as a superquadric with species-specific t (Table 3), lower part as a cylinder (RMSE: pine 15.9 m^3, spruce 23.9 m^3).



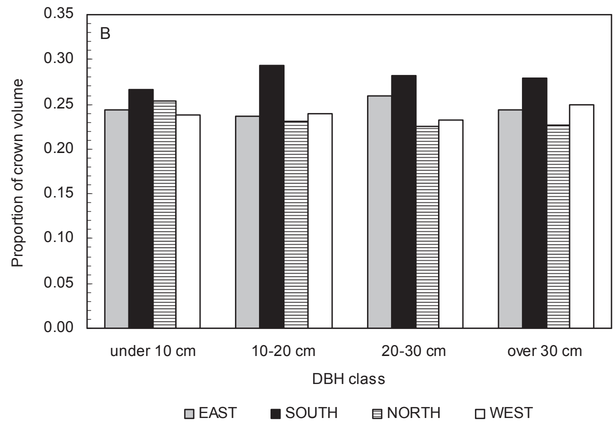


Fig. 4. Volume of crown quarters in DBH classes. A. Scots pine. B. Norway spruce. (The volume quarters for each DBH class and each cardinal direction were summed for all study trees.)

cm, 20.1–30.0 cm, >30 cm), and the volume quarters for each DBH class and each cardinal direction were summed for all trees (Fig. 4). In both species, the southern quarter did, indeed, become the largest in terms of volume as the trees increased in size. The crowns of small trees were relatively symmetric, but asymmetry increased as the trees became larger. However, the differences in the sizes of the quarters for spruce were larger than for pine, and started to appear already at an earlier stage. This may be a result of the slower growth rate of spruce. An interesting observation was in the size of the western quarter: in mature spruces, the eastern and western quarters were approximately the same size, whereas in mature pines the western quarter was clearly smaller than the eastern quarter. A summary of the crown volume development as a summed function of DBH classes is provided in Fig. 4.

4 Summary

This paper addressed crown shape modeling from the perspective of optical, passive remote sensing. In remote sensing applications, crown shape may be used in, for example, species recognition, to acquire information on general stand structure or allometric relationships needed for forest management purposes, or to model absorbed radiation and primary production over a forested area. We discussed the requirements of global crown shape models in optical remote sensing and field measurement techniques related to them, and presented a measurement and modeling study on the crown shape of Scots pine and Norway spruce. To be applicable in remote sensing over large areas, the crown shape models used need to be general and computationally efficient, but on the other hand, also have sufficient accuracy. Based on this case study, several pathways for estimating the volume of a pine or spruce crown for radiative transfer models used in remote sensing can be suggested. When only routine stand inventory (tree height, DBH) data exists, regression models can be used to predict crown maximum radius and length. Based on these basic dimensions, using an ellipsoidal shape for the crown is a practical solution. On the other hand, if a detailed inventory has been conducted and crown length and maximum radius have been measured, more reliable results will naturally be obtained in crown volume estimation. A tree-specific shape parameter describing the upper part of the crown (e.g. t) does not improve crown volume estimation for pine and spruce, but may have an important role as a species-specific characteristic to, for example, identify tree species from high resolution remotely sensed images.

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