The spectral signature of coniferous forests: the role of stand structure and leaf area index

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Academic dissertation

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ABSTRACT

Recently there has been an increasing interest in variables such as the leaf area index (LAI) that can be used to describe forest ecosystem processes and that can be obtained through optical remote sensing. The generic nature of remote sensing techniques and the wide range of spatial and temporal resolutions of the data sets make it possible to apply remote sensing in studying various processes and structure of a multitude of terrestrial ecosystems. The prerequisite for the development of any remote sensing application should nevertheless be an understanding of the physical principles behind the spectral signal measured by satellite- or air-borne instruments. The boreal forests of the northern hemisphere, dominated by coniferous tree species, form the largest unbroken forest zone in the world. From the perspective of remote sensing, a widely acknowledged, but poorly explained phenomenon is the generally observed lower spectral reflectances of coniferous forests when compared to broadleaved forests. The only alternative to explaining this phenomenon is studying the radiative transfer process in coniferous canopies. In this dissertation, the relationships of spectral and structural properties of boreal coniferous forests were investigated through empirical and simulation studies, and this new information was applied in LAI retrieval from optical satellite images over conifer-dominated areas in Finland. The first part assessed the effect of macro- and microscale grouping on the spectral signature of coniferous stands. Results indicated that crown size and shape are important factors influencing stand reflectance and that a main explanation for the low reflectances of conifer stands especially in the near infrared wavelengths is the high level of within-shoot scattering. The second part focused on estimating LAI from optical satellite images both using spectral vegetation indices and by inverting a physically based forest reflectance model. Both methods indicated their feasibility for LAI estimation. A general observation was that inclusion of the previously little-used middle infra-red wavelength in both retrieval methods slightly improves the remotely sensed LAI estimates for conifers.

Keywords: optical remote sensing, forest reflectance model, spectral vegetation index, crown shape, photon recollision probability.

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LIST OF ORIGINAL ARTICLES

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III. Rautiainen, M. & Stenberg, P. 2005. Application of photon recollision probability in coniferous canopy reflectance simulations. Remote Sensing of Environment, 96: 98-107.

IV. Peltoniemi, J., Kaasalainen, S., Näränen, J. Rautiainen, M., Stenberg, P., Smolander, H., Smolander, S. & Voipio, P. 2005. BRDF measurement of understory vegetation in pine forests: dwarf shrubs, lichen and moss. Remote Sensing of Environment, 94: 343-354.

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VIII. Stenberg, P., Rautiainen, M., Manninen, T., Voipio, P. & Smolander, H. 2004. Reduced simple ratio better than NDVI for estimating LAI in Finnish pine and spruce stands. Silva Fennica, 38 (1): 3-14.

Study I: Rautiainen was responsible for the simulations and had a leading role in writing the paper. Stenberg, Nilson and Kuusk participated in writing the paper.

Study II: Rautiainen developed the measurement design and carried out the field work and data analysis, and had a leading role in writing the paper. Stenberg contributed to writing the paper.

Study III: Rautiainen had a major role in collecting the field data. She did the simulations and had a leading role in writing the paper. Model development was done jointly by Rautiainen and Stenberg, who also participated in writing the paper.

Study IV: Field work and data analysis were carried out by Peltoniemi, Kaasalainen and Näränen. Rautiainen contributed to writing the paper.

Study V: Rautiainen planned the field work and had a major role in collecting the data. She analyzed the data and had a leading role in writing the paper. Stenberg and Nilson contributed to writing the paper.

Study VI: Rautiainen was the single author.

Study VII: Rautiainen had a major role in collecting the field data. She did the simulations and had a leading role in writing the paper. Stenberg, Nilson, Kuusk and Smolander participated in writing the paper.

Study VIII: Rautiainen had a major role in collecting and analyzing the data. Stenberg had a leading role in writing the paper.

CONTENTS

1. INTRODUCTION

1.1. Remote sensing in ecology

Many ecological studies and applications require extensive geographical data sets which are difficult to collect with field measurements. Remotely sensed data can be used from local to global scales in characterizing various ecological variables that are applicable in monitoring, for example, changes in land and vegetation cover, land use, vegetation structure, phenological cycles, natural disasters or biodiversity of habitats. The generic nature of remote sensing techniques and the wide range of spatial and temporal resolutions of the data sets make it possible to apply remote sensing in studying the processes and structure of a multitude of terrestrial ecosystems such as forests, agricultural fields, wetlands and urban vegetation. It is also important to acknowledge the interactions between different parts of the biosphere, and thus obtaining simultaneous time series data from vegetation, oceans and atmosphere helps us assess many global environmental phenomena.

During the past few decades, a considerable international effort in satellite image interpretation methods has been placed on estimating forest resources needed for commercial purposes i.e. timber growth and harvest planning. From the forestry perspective, sustainable forest management practices and international commitments to reporting on sustainability issues are now gradually taking over and place a need for detailed information. From a more general ecological point-of-view, the influence of climate change, land use changes, temporal ecosystem dynamics and stresses set a requirement for assessing indicators of these processes at large geographical scales. Energy, water and gas exchanges between the atmosphere and land surfaces are controlled by biophysical properties of vegetation, and thus influence our climate at different scales (e.g. Bonan, 1995, Cannell, 1989). Therefore, there is an increasing interest in variables that describe the function and ecosystem processes of forests and other vegetation types. For example, net primary production (NPP), the difference between accumulative photosynthesis and accumulative autotrophic respiration of green plants (per unit time and space) (Leith & Whittaker, 1975) which is used to quantify the net carbon assimilation rate by living plants, is one variable of interest that provides synthesized information on an ecosystem. Data needed for these estimates include as one of the most important leaf area index (LAI), which characterizes ecosystem status and is used to drive many ecosystem models (e.g. Turner et al. 2003, Liu et al. 1997, Bonan, 1995, Running & Coughlan, 1988). Leaf area index itself is a dimensionless variable that is defined as the one-sided or hemisurface (half of total) green leaf area per unit area of ground (Chen & Black, 1992) and can also be, for example, used to characterize changes in vegetation from global (e.g. Myneni et al. 1997a) to local (e.g. Olthof et al. 2003) scales since it responds rapidly to changes in climatic conditions or environmental stress factors.

Biophysical variables, such as the leaf area index, fraction of absorbed photosynthetically active radiation (fPAR) or percentage green cover, are typically not included in traditional forest inventories since methods for measuring them are yet under development and perhaps also because their ecological importance has not been fully understood early on. Biophysical variables are defined here in a limited sense as those state variables which directly control the radiative transfer process in vegetation canopies. Ever more efficient computer processing techniques and sophisticated satellite instruments enable the reduction of the costs of monitoring both biophysical and traditional forest inventory variables compared to previous decades. In theory, the requirements for estimating these variables from remotely sensed spectral data are simple to list (Goel, 1989): (1) solar radiation has interacted with the vegetation and has then been recorded by a (satellite or air-borne) sensor, (2) the reflected signal carries in it the spectral signature of the vegetation and (3) this signal can be deciphered to obtain properties of the stand. If the modeled relationship is to be applied over larger regions or different satellite or air-borne sensors, it should be based on a physically relevant phenomenon. In other words, understanding how the optical and geometrical properties of the vegetation result in the measured signal should be a requirement for any application. A central task in remote sensing is therefore to understand the physics behind the radiation signals measured in space and to apply this knowledge in developing instruments and computation methods for interpreting satellite images.

1.2. Spectral properties of vegetation

The reflected spectral signal of vegetation measured by a sensor placed below the atmosphere can be considered to be a result of three factors: the incoming solar radiation field, the optical properties of phytoelements and other plant parts, and the three dimensional structure of the plant stand. The physiological basis of the spectral properties of vegetation is how plants have developed to adapt both their internal and external structure and pigmentation to photosynthesis.

First, the role of the incoming radiation field should be considered. In this case, we are interested in shortwave solar radiation which constitutes 98 % of all solar radiation reaching Earth (Campbell, 1981). It is in the spectral range of 280 to 4000 nm, and can be divided into direct and diffuse components (Ross, 1981) depending on whether the radiation has undergone scattering with atmospheric particles or not. Visible radiation is between 400 and 700 nm and after 700 nm, the wavelength range is called the near infrared region. At solar elevation angles larger than 10º, the spectrum of incoming radiation is relatively uniform for radiation between 400 and 800 nm, i.e. the portions of radiation at different wavelengths in this range are similar (Smith & Morgan, 1981). At lower sun elevation angles, the portions of blue and the lower end of the near-infrared radiation (NIR) increase. Usually in practical applications, the solar elevation angle is larger than 10º during spectral measurements.

When the nature of the incoming radiation has been determined, the optical properties of phytoelements should be considered next. To begin with, vegetation does not behave like a Lambertian surface i.e. it is an anisotropic scatterer. How the external and internal structure of leaves reacts with electromagnetic radiation is a main driving factor of the intensity and directional properties of the spectral signal. The original incident radiation on a leaf is divided into the spectral hemispherical reflectance, transmittance and absorption of a leaf (Fig. 1). Typically, only approximately 2 to 3 % of the radiation which initially is incident on the leaf surface is immediately (without entering the leaf) reflected from the leaf surface (Tucker & Garratt, 1977). The amount, specular portion and directional distribution of it depend on the species-specific structure of the leaf surface (Horler & Barber, 1981).

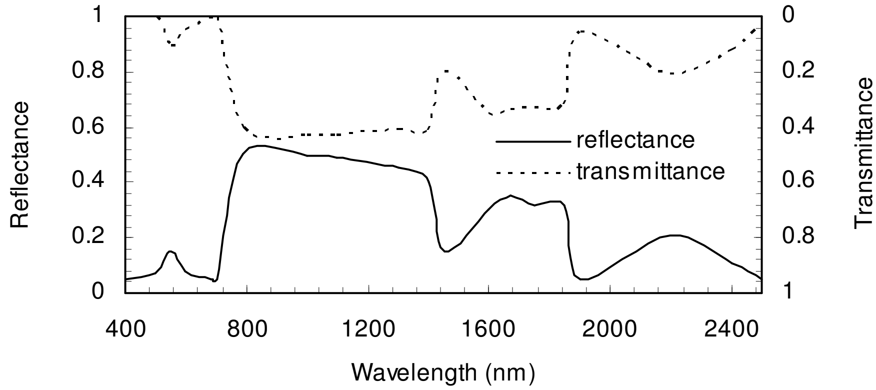

Figure 1. Reflectance and transmittance spectra of a typical fresh, green leaf. Redrawn according to Jacquemoud et al. (1995b) where the spectra were produced as an average of leaves from 50 plant species.

The radiation that is not immediately reflected, but enters the leaf, can logically have three fates: it can once again be reflected upon scattering inside the leaf, it can be absorbed or it can be transmitted to the hemisphere opposite the incident direction. The fate of the radiation will now depend on its wavelength region. In the visible region, a relatively small amount of the incident radiation is reflected or transmitted by leaves – the radiation is mainly absorbed by pigments called photoreceptors. The most important of these photoreceptors are chlorophylls *a* and *b* which complement each other, chlorophyll *a* being the more abundant receptor (McDonald, 2003). Their absorption maxima are approximately at 400 to 500 nm (the blue-violet region) and at 600 to 700 nm (the orange-red region). Other important pigments are xanthophylls and carotenes.

The rapid change in reflectance at the interface of the red and near infrared regions is called the "red edge". The plant strategy for high scattering of NIR radiation is explained by the fact that if also this radiation was absorbed as efficiently as the photosynthetically active radiation, the energy contained in the NIR radiation would heat and destroy the internal protein structure of the leaves. Physically, NIR radiation scatters from the leaf spongy mesophyll (Walter-Shea & Norman, 1991). After the NIR region, in the middle-infrared region (MIR, defined here as the region after approximately 1300 nm), reflectance and transmittance decrease when compared to the NIR region. In this region, the scattering processes are controlled by leaf water content and internal structure (Knipling, 1970) i.e. if the water content of leaves decreases, MIR reflectance increases.

Several optical models have been developed for calculating leaf reflectance and transmittance. Perhaps the most popular of the more recent models in the remote sensing community has been the PROSPECT model, a generalized plate model based on leaf biochemical composition (Fourty et al. 1996, Jacquemoud & Baret, 1990). Other models include LIBERTY (Dawson et al. 1998) and LEAFMOD (Ganapol et al. 1998). These models can be used as submodels to simulate leaf optical properties in models created for simulating the reflectance or transmittance properties of a whole stand.

The optical properties of leaves can be measured and are important, but only partly account for the spectral signal of a vegetation stand. Leaf optical properties, produced by leaf biochemical properties, are often enhanced only at high leaf area index values (Baret et al. 1994) and are thus less important at lower leaf area index values. Variability in canopy structure, on the other hand, has the dominant control on canopy reflectance (e.g. Asner, 1998). The larger and more heterogeneous the vegetation element or stand, the more complicated measuring scattering properties of it becomes. The reason for this is that geometrical factors play a major role in modifying stand reflectance and transmittance. Traditionally, measurements and modeling in this field have concentrated on agricultural crops, not trees or forests, since the geometrical structure of crop stands is possible to measure in a limited amount of time, the topography of the area is easy to model and the stands are often homogeneous over large areas as well as easily accessible. Nevertheless, whether we are characterizing cultivated crops or forest, there are several structural variables that are common for all vegetation stands in describing their geometry. The shapes, inclination angles, distribution patterns and leaf area density, grouping of leaves of different hierarchic scales, canopy shape (e.g. plant or crown shape) and canopy gap fraction are factors which alter the spectral signature of the stand (e.g. Asner, 1998).

In addition to the canopy structure itself, it must be noted that general features of the landscape i.e. topography also influence the reflected signal. Also, for any person making observations on the general appearance of, for example, boreal forests it is clear that the reflected signal is influenced by the abundant understory vegetation (dwarf shrubs, grasses and regenerating tree seedlings) and the ground which is typically covered by a thick moss layer. This has been noted as an important factor in several studies in coniferous regions (e.g. Böttcher, 2003, Brown et al. 2000, Chen et al. 1999, Miller et al. 1997, Chen & Cihlar, 1996, Nilson & Peterson, 1994, Spanner et al. 1990). Thus, understanding the changing role of canopy cover in various viewing and illumination angles and the amount and spectral properties of the understory or soil are crucial for interpreting the reflected signal.

The angular properties of the reflected signal are other factors which make the interpretation of spectral signatures of heterogeneous stands, such as forests, more complicated. The spectral signal is typically referred to as a bidirectional signal – it is a function of the prevailing sensor viewing and solar geometric characteristics. Depending on these conditions, the target stand can look darker or brighter. The most obvious this effect becomes when the viewing and illumination angles overlap (in the same plane) and a hot spot effect is formed. However, it is not only the angular properties of outgoing radiation that should be understood. The angular distribution of downward radiances is also of significance as it governs the irradiance at ground level. For example, assuming that sky radiance is anisotropic in clear sky conditions can be a considerable source of problems in reflectance modeling (Kuusk et al. 2002).

Simulation studies have been carried out to understand radiative transfer in simplified plant stands or for agricultural crops. However, as described above, forests are structurally more complicated and heterogeneous, and fewer radiative transfer studies using empirical data have been carried out in them. Therefore, a clear need exists for linking with a physical understanding the spectral properties and structure of forests.

1.3. Spectral characteristics of coniferous forests

The boreal forest zone of the northern hemisphere, also referred to as taiga, is the largest unbroken forest zone in the world and accounts for approximately one fourth of the world's forests. Boreal forests spread mainly through Canada, the United States (Alaska), Russia and Fennoscandia. The zone represents a major global store of carbon and thus plays an important role in regulating global climate. Conifers, adapted to the cold and drought conditions of winter, are the dominant tree species. Large regions of the boreal zone are inaccessible and therefore, it is remote sensing that presents the only feasible method for acquiring information on the status of the vegetation of extensive areas. However, currently the understanding of the spectral behavior of this zone, particularly of the coniferous canopies, is limited and remote sensing faces many challenges, beginning from obtaining the training data sets needed for developing the remote sensing methods. Chen and others (1997) have listed general reasons for why ground-comparison measurements in the conifer-dominated boreal forests are more difficult than measurements of plantations or agricultural fields: the inherent difficulties of measuring forests, current lack of standards for measurements, the difficulty of distinguishing between the influence of various components (e.g. green leaves and woody material) on the radiation transmitted by canopies in measurements, and the problems related to generalizing local measurements to larger areas. Even though these reasons can be considered valid also for other forest landscapes, they do highlight the difficulty of gathering empirical data.

What then is so special about the spectral signature of coniferous forests? A widely acknowledged, but poorly explained phenomenon is the generally observed lower reflectances of coniferous forests when compared to broadleaved forests - why are the reflected spectra of coniferous forests which have the same leaf area and age structure so distinct from similar broadleaved forests? Seeking answers to this question requires physically based understanding of the radiative transfer process in coniferous canopies. Relatively recently, several studies on the relationships of biophysical variables and boreal coniferous forest reflectances have been carried out in Canada in the species-rich forests (e.g. Chen et al. 2002, 1999, Chen & Cihlar, 1996) and only a few in the species-poorer Northern Europe in the more easily accessible areas (Eklundh et al. 2003, Gemmell et al. 2002, Eklundh et al. 2001, Gemmell & Varjo 1999, Gemmell, 1999, Nilson et al. 1999, Strandström 1999, Nilson & Peterson, 1994). Many studies have been conducted mainly with the purpose of relating biophysical variables through empirical regression for leaf area index mapping purposes. Only a few studies have actually presented physically based approaches to applying or interpreting the spectral signatures of boreal coniferous stands (Wang et al. 2004, Böttcher, 2003, Gemmell et al. 2002, Eklundh et al. 2001, Lacaze & Roujean, 2001, Gemmell & Varjo, 1999, Leblanc et al. 1999, Chen & Leblanc, 1997, Muinonen, 1995, Li & Strahler, 1985). In general, the focus of these studies has either been on model development or model application for estimating biophysical parameters. Therefore surprisingly, even though these studies exist, it is difficult to find any clear, general and published explanations (or speculations) on the specific causes of the large difference in the spectral signature of broadleaved and coniferous canopies.

Scientists have been careful in making statements of the spectral differences, and thus currently, several, very general explanations have been offered to explain the observed lower reflectances of coniferous forests in comparison to broadleaved forests. The tree crown surface of coniferous stands is more uneven than that of broadleaved species (Häme, 1991) - when surface roughness (macroscale clumping) increases, shaded area within the canopy increases and reflectances decrease in all wavelengths. The depth and high needle area density of coniferous canopies have also been mentioned as a possible reason (e.g. Seed & King, 2003), which is credible since according to a review by Jonckheere and others (2004), the highest leaf area index values that have been reported are from coniferous canopies. A high level of within-shoot scattering of conifers has been noted already three decades ago (Norman & Jarvis, 1975), without, however, being implemented in practice in models. Absorption by coniferous needles has been recorded to be higher than that by broadleaved species (Roberts et al. 2004, Williams, 1991), a phenomenon which should result in lower reflectances. These, even though only few, studies offer us the basis for further, more detailed investigations and emphasize the importance of various geometric properties as the main driving factor of the differences between broadleaved and coniferous stands. However, none of these studies were aimed specifically at giving a quantified or detailed physical explanation of the mechanisms that account for the differences, but remained rather descriptive. Therefore, there is a need for exploring the relationship of structural properties of coniferous forests and how they influence the spectral signal.

What are then the conifer-specific geometric properties that should be examined? Since the previously mentioned explanations for the differences in spectral behavior remain rather vague, we can turn to, for example, photosynthesis research to look for potential specific geometric properties that have been identified as important for the amount and distribution of intercepted radiation in coniferous stands and that could be studied also in remote sensing applications. To begin with, it is obvious that the importance of the spatial distribution of needles in determining the radiative regime of coniferous canopies must be acknowledged and that the foliage distribution patterns can be considered at several structural levels (e.g. whole canopy, crown, branch, shoot) (e.g. Cescatti, 1997b, Nilson, 1992, Norman & Jarvis, 1975, 1974). Shoot geometry (grouping of needles into shoots) has been observed to have a large impact on the efficiency with which coniferous shoots intercept light (Smolander et al. 1994, Oker-Blom et al. 1991, Oker-Blom & Kellomäki, 1983). At a higher hierarchy level, crown shape and the related spatial shadow patterns have been acknowledged as a generally important factor for radiation intercepted by a canopy (e.g. Kuuluvainen & Pukkala, 1989, 1987, Oker-Blom & Kellomäki, 1982, Horn, 1971). However, these properties have been studied very little in remote sensing of coniferous forests and can be presumed to be the cause of more complicated radiative transfer processes in the case of scattered radiation than in the case of intercepted radiation. Therefore, it is justified to examine these properties also in vegetation reflectance studies and investigate if it is possible to obtain a more profound understanding of their influence on the remotely sensed signal.

1.4. Aim and structure of this dissertation

The theme explored in this dissertation is the formation of the spectral signature of boreal coniferous forests and application of this information in leaf area index retrieval from optical satellite images.

The primary aim of the dissertation was to evaluate the effect of so-far unexplored canopy properties - two aspects of phytoelement grouping - on the radiation reflected from coniferous forest stands. Understanding the role of stand properties in forming forest reflectance is of pure scientific interest as well as crucial for the development of remotely sensed retrieval methods of various vegetation properties. Thus, the second aim of the dissertation was to test the use of two types of retrieval methods, those utilizing satellite images and stand properties in the technique (as in various physically based forest reflectance models) and those using only satellite images, for a currently widely interesting vegetation biophysical variable, the leaf area index.

Structurally, the dissertation can be divided into two parts comprising eight studies with their specific aims as follows:

- The first part of the dissertation was dedicated to the assessment of the effect of three factors influencing the spectral signal of coniferous forests: macro- and microscale grouping and understory vegetation (Fig. 2). First, one aspect of macroscale grouping, the effect of tree crown shape on the reflectance of coniferous canopies (Study I), was evaluated using a physically based forest reflectance model. This was followed by development of a crown shape measurement technique and an empirically based crown shape model for Scots pine (*Pinus sylvestris* L.) to support forest reflectance modeling (Study II). After this, the influence of microscale grouping, i.e. clumping of needles into shoots, on coniferous canopy reflectance was explored using a new forest reflectance model (Study III). Finally, to promote the understanding of the influence the vegetation below the trees has on the spectral signal of coniferous forests, the bidirectional reflectance distribution functions (BRDFs) of common boreal understory species were measured (Study IV) and canopy cover of Scots pine stands was assessed with different methods (Study V).
- The second part of the dissertation was dedicated to estimating leaf area index of coniferous stands (dominated by Scots pine and Norway spruce (*Picea abies* (L.) Karst.)) located in Finland from optical satellite images: Landsat 7 ETM and SPOT HRVIR1. First, a physically based forest reflectance model was used to retrieve leaf area index (Studies VI, VII). This was followed by testing spectral vegetation indices in leaf area index mapping over three study areas (Studies VI, VIII).

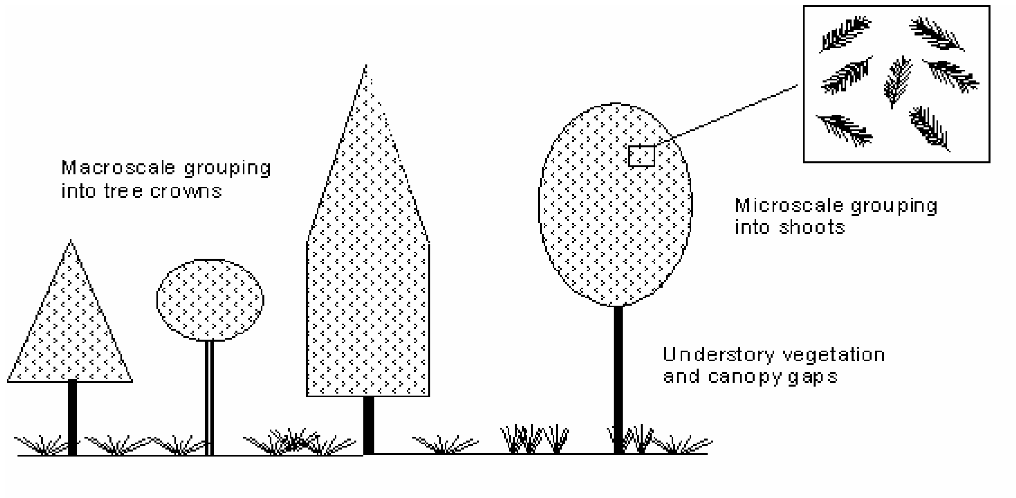

Figure 2. The three factors influencing the spectral signal of coniferous forests that are investigated in this dissertation: macro- and microscale grouping and understory vegetation.

2. THE SPECTRAL SIGNATURE OF FORESTS: METHODOLOGY AND APPLICATION

2.1. Forest reflectance models

A forest reflectance model is a method for describing the outgoing radiation field of a forest. The models can be used (1) to understand how the spectral signature of a stand is formed, (2) to simulate seasonal and age courses in forest reflectances, (3) to investigate quantitative relationships between remotely sensed reflectance data and forest attributes, and (4) to create an interface between standard forestry data bases and satellite images for reflectance model inversion purposes (Nilson et al. 2003). Simulation studies done with these models can serve as a method of carrying out experiments (sensitivity analyses) which are difficult or even impossible to conduct in natural conditions. In this way, we can try to identify the most important factors influencing the spectral signature of a given forest type. This information can then be used for developing both empirical, statistical and physically based retrieval methods for vegetation variables from optical satellite images under varying illumination and viewing conditions. The strength of physically based forest reflectance models also lies in that they are not site-, sensor- or season-specific in the way purely statistical methods can be.

A problematic concept in canopy reflectance modeling is the concept of "physically based" - it is addressed differently by different scientists. For example, Knyazikhin and others (1998b) emphasize that a model is physically based only when it does not violate the law of energy conservation i.e. the sum of lost and gained spectral radiation fluxes in the vegetation is zero. On the other hand, in models where the important hot spot effect, a strong peak in the reflected signal when the angle of illumination and viewing are the same, (Jupp & Strahler, 1991, Kuusk, 1991a), the made approximations could give rise to violations of the energy conservation law. Nevertheless, these models often describe the three dimensional structure of the stands in a more realistic way. Perhaps a more relaxed definition for physically based could thus be that the model aims at accounting for, at least partially, the physical phenomenon behind scattering of solar radiation in a plant stand. Using such a definition would better allow making a distinction to the fully statistically based methods.

The choice of a forest reflectance model or the way it is developed depends ultimately on the application purpose. As in any models, the fewer input parameters are required, the easier it is to apply to measured data since field work time is saved. Roughly speaking, the more complicated reflectance models are usually suited for learning purposes and the simpler models for larger area mapping purposes. The simple models are typically close to the models used for agricultural crops, whereas the complex models have been developed for forest modeling purposes right from the beginning. Forest reflectance modeling is a wide topic with many detailed issues related to modeling specific forest components (e.g. leaf optics, hotspot or soil properties) and I will only provide a brief overview of the models here as an introduction to the model application and development work presented in this dissertation.

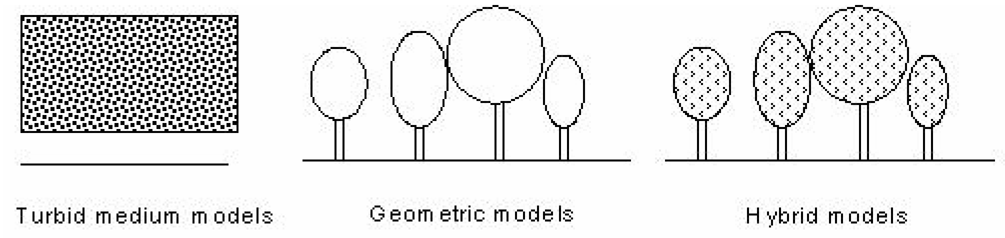

Figure 3. A simplified scheme of the development of forest reflectance models from turbid medium to hybrid models.

Forest reflectance models can be divided into four main categories depending on their computation methods and the way they describe a stand: Monte Carlo models, turbid media models, geometric models and hybrid models (Fig. 3) (Goel 1989). In Monte Carlo models, rays of photons in the three-dimensional media and the photon fates in reflectance, transmittance and absorption are simulated in macroscale foliage volume envelopes. Examples of such models are DRAT and ARARAT (Lewis, 1999), FLIGHT (North, 1996) and RAYTRAN (Govaerts & Verstraete, 1998).

Turbid medium models, where the substance is like a green "cloud" of planary elements i.e. green leaves, are usually better suited for grasslands and agricultural crops, since typically the canopy is described as one-dimensional and varies only with height above the ground. In these models, which typically use leaf area density, leaf orientation distribution and leaf scattering phase function as input, the radiative transfer equation (Chandrasekhar, 1950) has been solved using different approximations (e.g. Suits, 1972, Verhoef, 1984, Myneni et al. 1992). Often one-dimensional models do not have the sufficient heterogeneity of output that is required for learning to understand how the signal of a complex vegetation stand is formed. Nevertheless, the simplicity of turbid media models in terms of input data makes them a feasible option for e.g. global mapping purposes. An example of such an operational, generalized reflectance model is the one used for processing data from MODIS images into global leaf area index maps every eight days (Knyazikhin et al. 1998 a, b).

Geometric and geometric-optical models represented a new era in reflectance modeling upon their arrival, their approach being more complicated and forest structure-based than in the turbid medium models (e.g. Gerard & North, 1997, Li & Strahler, 1992, 1985, Strahler et al. 1984). These models have several differences to the previously more common or conventional, radiative-transfer based models. Forest stands are modeled as three-dimensional, distinct objects on a contrasting background and are then viewed and illuminated from different angles in the hemisphere. These models have been highly productive in explaining a major part of the bidirectional reflectance distribution function (BRDF, the ratio of reflected radiance to incident irradiance at given illumination and viewing angles) of a forest stand (Strahler & Jupp, 1991) and emphasizing the importance of acknowledging three-dimensional macroscale clumping whenever it is datawise possible. However, they simplify the multiple scattering that occurs within the vegetation.

Hybrid models are the most recent in the development sequence. However, at Tartu Observatory, where one of the well-known hybrid models was developed, the stage of geometrical models did not exist. Hybrid models combine features from turbid medium and geometric models: a forest stand is modeled as geometric objects (tree crowns) with a given tree distribution pattern and, as a difference to the geometric-optical models, an internal architectural structure in the tree crowns. The internal structure of crowns is believed to be a significant factor in determining the directional reflectance behavior of a canopy (e.g. Chen & Leblanc, 1997), and thus the internal structure of the tree crowns in these models can range from a turbid medium to some level of grouped architecture (e.g. Lacaze & Roujean, 2001, Kuusk & Nilson, 2000, Chen & Leblanc, 1997, Li et al. 1995, Nilson & Peterson, 1991) with mathematical complexity and computation time increasing simultaneously with the degree of grouping.

The considerable number of models in this field makes comparison of the models interesting as well as an important process. An example of such an exercise is the Radiative Transfer Model Intercomparison (RAMI) (Pinty et al. 2000) in which model developers may voluntarily participate. The participating models perform a variety of simulation runs under specified illumination and viewing conditions for geometrically and spectrally well-defined plant stands and submit the results to a common database which is then used for plotting comparative graphs. In general, the models have captured main reflectance features of the given stands in a similar way, but also several sources of differences (e.g. treatment of leaf size effects, leaf angle distributions) have been noticed and have then resulted in modifications of some of the participating models.

In this dissertation, two forest reflectance models are used: the hybrid type Kuusk-Nilson model (Kuusk & Nilson, 2000, 2001) and a semi-physical parameterization model, PARAS, which is newly introduced here. (The term “semi-physical” is explained by the limitations of the model which are described later on.) The models serve as a tool to study conifer-specific features of grouping. The Kuusk-Nilson model was chosen since it requires a sufficiently large input set of basic forest inventory variables to be useful in sensitivity analyses that are of interest in forestry and has structurally been developed to be applicable especially in sub-boreal and boreal regions. The model was used to study one aspect of macroscale grouping in coniferous forests i.e. the effect crown shape has on the reflectance of stands (Study I). The effect of microscale grouping i.e. grouping of needles into shoots, on the other hand, was studied using the PARAS model which was specifically developed for this purpose (Study III).

The following terminology, according to Martonchik and others (2000), will be used in the description of the models and measurements. Ignoring wavelength dependence, the bidirectional reflectance distribution function (BRDF) is a function of the zenith and azimuth angles of reflection (θ_r, ϕ_r) and illumination (θ_i, ϕ_i), respectively:

$$BRDF = \frac{dL_r(\theta_i,\phi_i;\theta_r,\phi_r)}{dE_i(\theta_i,\phi_i)}(sr^{-1}) \qquad \text{(Eq. 1)}$$

where dL_r is the radiance reflected into the given solid angle and dE_i the irradiance from the illumination direction. The bidirectional reflectance factor (BRF) is the ratio of flux scattered into a given direction by a surface under particular direct radiation, to the flux scattered in the same direction by an ideal Lambertian scatterer under the same conditions. It is calculated simply as the product of π and the BRDF of the target surface. Hemispherical-directional reflectance factors (HDRFs), on the other hand, are BRFs except that illumination is allowed from the entire upper hemisphere, not only from a given direction. In other words, BRF is equal to HDRF when the diffuse incoming component is zero. Formally, HDRF is defined as a function of the zenith angle θ_r and the azimuth angle ϕ_r of reflection:

$$HDRF(\theta_r, \phi_r) = \frac{d\Phi_r(\theta_r, \phi_r)}{d\Phi_r^{Lambertian}} \qquad \text{(Eq. 2)}$$

where $d\phi_r^{Lambertian}$ the flux reflected from an ideal surface. In narrative text, the functions will be referred to as "reflectances" or "reflectance factors".

The directional, multispectral Kuusk-Nilson model includes properties of both geometric-optical and radiative transfer equation based models. It requires input on stand structure as well as understory and ground reflectance properties, and can simulate reflectances (hemispherical-directional reflectance factors, HDRF) in the wavelength range of 400 nm to 2400 nm at 1 nm spectral resolution. The HDRF (denoted by R) of the forest stand is in the model calculated as the sum of three components:

$$R = R_{CR}^1 + R_{GR}^1 + R_{CR+GR}^{m+d} \qquad \text{(Eq. 3)}$$

where R_{CR}^1 and R_{GR}^1 are the portions of the HDRF caused by single scattering of direct radiation from the crowns and ground, respectively, and R_{CR+GR}^{m+d} is composed of multiply scattered direct radiation from crowns and ground, and the reflectance (single and multiple scattering) of diffuse sky radiation. The portion of diffuse down-welling flux of total down-welling flux is calculated for every spectral channel with respective modules of the 6S atmosphere radiative transfer model (Vermote et al., 1997).

I will now briefly describe the calculation of the components in Eq. 3. The first component, single scattering from crowns (R_{CR}^1) is calculated from the radiance of a single tree (see Kuusk, 1991b), accounting for mutual shading and screening of tree crowns in a stand:

$$R_{CR}^1 = c \quad \lambda \int \int_V \int u(x,y,z)\Gamma(r_1,r_2) \quad p_{00}(x,y,z;r_1,r_2) \quad dxdydz \ / \cos\theta_1 \qquad \text{(Eq. 4)}$$

where λ is stand density, u is the foliage area density within the crown, Γ is the area scattering phase function of leaves, p_{00} is the bidirectional gap probability, r_2 is the view direction, r_1 is the Sun direction and θ_1 denotes the solar zenith angle (Nilson, 1991). The parameter c in Eq. 2 marks the spatial tree distribution pattern and can be calculated from Fisher's grouping index (GI) (Nilson, 1999). It is equal to one, when the tree crowns have a Poisson distribution, greater than one for more regular stands, and less than one for more clumped stands. In calculating the gap probabilities, a uniform distribution of spherically oriented shoots within the crowns is assumed and the effect of the grouping of needles into shoots is described by a grouping parameter (i.e. a needle clumping index). However, no shoot scattering phase function is included in the model and thus the model may give too high multiple scattering reflectances. The leaf scattering phase function is assumed to be bi-Lambertian with an additional specular reflectance component (see Nilson, 1991).

The second component, single scattering from ground (R_{GR}^1), is formed of radiation reflected from sunlit understory and soil, and is simulated with the two-layer canopy reflectance MCRM2 model (Kuusk, 2001) incorporated in the Kuusk-Nilson forest reflectance model. The third component in the model, R_{CR+GR}^{m+d} , includes multiple scattering of direct radiation from crowns and ground and the scattered radiance of diffuse sky radiation. It is modeled more approximately (i.e. more emphasis is on the modeling of single scattering), with all foliage distributed in a horizontally homogeneous layer i.e. separate trees, shoots or branches are not distinguishable.

Crown shape and tree distribution pattern are accounted for only approximately. Crowns can be modeled as azimuthally symmetric ellipsoids, cones or cylinders with a conical upper part. The effective leaf area index value (LAI_{eff}) is used in the calculations of diffuse fluxes instead of the real leaf area index, and is calculated from the gap probability in a given direction, which depends on foliage orientation, the tree distribution pattern and crown shape. The concept of effective leaf area index has risen also in connection with the commercial instruments which measure and calculate leaf area index indirectly from Beer's law and radiation transmitted by a canopy. This definition assumes a random spatial distribution of leaves and, for conifers, due to clumping, underestimates the true leaf area index.

Stand structure in the reflectance model is characterized by relatively basic forest inventory parameters: stand density, tree height and breast height diameter, crown length and radius. In addition, the canopy structure is described in more detail with crown shape (ellipsoid, cone, or cylinder + cone), canopy leaf area index, needle (or leaf for deciduous trees) clumping index, branch area index (BAI) and needle reflectance and transmittance coefficients, which are calculated with the PROSPECT2 model (Jacquemoud et al. 1995b). Species-specific tree bark spectra are tabulated in the model based on measurements.

The Kuusk-Nilson model was used to examine the effect of crown shape on the reflectance of Norway spruce and Scots pine stands with an age range of 20 to 100 years first assuming ellipsoidal and conical crowns (Study I). Simulations were done at three wavelengths red (661 nm), NIR (838 nm) and MIR (1677 nm).

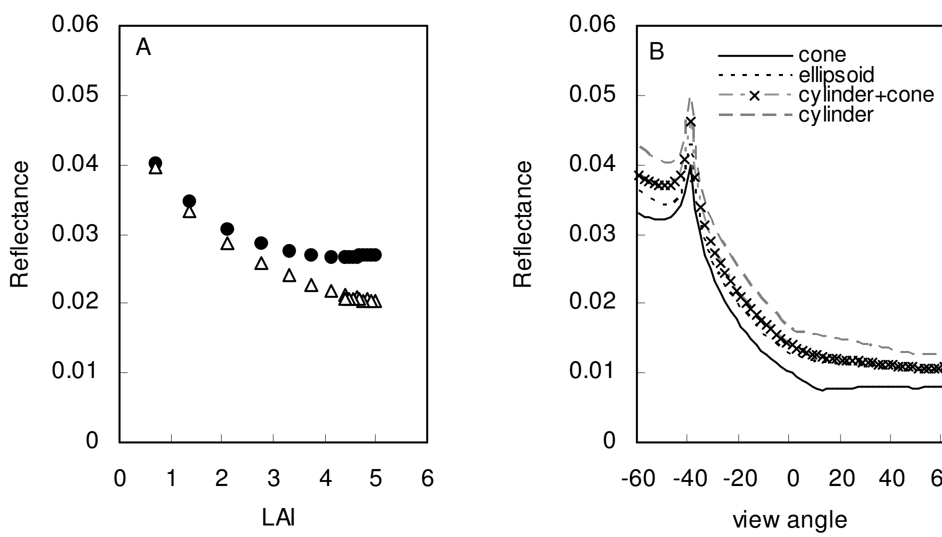

Figure 4. An example of the effect of crown shape on the reflectance of Scots pine stands at 661 nm (red wavelength). A. Simulated reflectance of an age course of stands (with different leaf area indices) modeled with two crown shapes (circles = ellipsoids, triangles = cones) (For more details, see Fig. 4a in Study I). B. The size of the component for single scattering from tree crowns for four crown shapes for a young Scots pine stand with a leaf area index of 2 (For more details, see Fig. 7a in Study I).

Results showed that crown shape is an important determinant of the reflectance of a coniferous stand: when a stand was modeled with conical crowns, it had a smaller reflectance factor than the same stand with ellipsoidal crowns (Fig. 4). More specifically, considerable differences in red reflectances between four different crown shapes (cone, cylinder, ellipsoid, and cylinder bottom, cone top) were observed for two pine stands with different leaf area index and canopy closure values. The larger the crown volume, the higher was the canopy reflectance at similar leaf area index and canopy closure. A comparison of the two stands revealed that in denser stands (with a higher canopy closure) single scattering from tree crowns was responsible for the difference in HDRF between the different crown shapes, whereas in stands with a smaller canopy closure the single scattering from ground dominated the HDRF.

From the results of the simulation study it is not possible to conclude which crown shape is the most correct for each species. For this purpose, measurements of crown shape are needed. Once empirical information on crown shape is available, it is finally possible to assess the errors present in simulated stand reflectances generated by incorrect or approximated crown shape. Therefore, as a logical follow-up to this study, a simple, measurement-based crown shape model was derived for Scots pine in order to provide justifications for the choice of crown shape in future practical applications (Study II). Crown profiles of 260 trees were measured and then modeled with curves of the Lamé family (also called superquadrics), which have been found useful for crown shape modeling also in previous investigations (Cescatti, 1997a, Koop, 1989). The model was originally planned so that crown shape could be generated from a routine forestry data base (including at minimum breast height diameter and tree height) and would thus require no extra measurements if the forest reflectance model is run using a standard data base supplied by an inventory organization. For the data collected in this experiment, crown shape above the maximum radius of the crown was close to a cone, and for individual trees, the maximum radius and its height were linearly related to breast height diameter and tree height. However, a major reservation related to the crown shape model should be noted – the shape parameter itself was not related to the stand variables (or tree age). Therefore, if further measurements from a wider range of geographical areas are not made, only average shape coefficients are available for use. On the other hand, as stand inventory data are usually available at stand level, not individual tree level, it is justified to use also an average shape coefficient for a stand if it is available. The error in the crown shape predicted by the model was assessed by comparing volumes of the measured and modeled crowns since crown volume together with crown shape were identified as important factors governing stand reflectance in Study I. The model performed well and the differences in the crown volumes were considered acceptable, especially taking into account the simple and light input requirements of the model.

Moving on from crown scale grouping effects into finer scale canopy architecture, the effect of shoot scale grouping on the reflectance of coniferous forests was studied (Study III). For this purpose, a new semi-physical parameterization model, PARAS, was developed in this study. The model uses a relationship between the so-called photon recollision probability and leaf area index for simulating forest reflectance. The recollision probability (p) is a spectrally invariant (i.e. wavelength independent) canopy structural parameter, which can be interpreted as the probability by which a photon scattered (reflected or transmitted) from a leaf or needle in the canopy will interact within the canopy again (Smolander & Stenberg, 2005). In a broadleaved canopy with flat leaves, a photon scattered from a leaf will not interact with the same leaf again, whereas in a coniferous canopy a photon scattered out from a shoot (collection of needles) may have interacted with the (different needles in the) shoot several times. At canopy scale, it has been shown that the spectral scattering coefficient $s(\lambda)$ of a canopy (photons of a specific wavelength scattered upward or downward from the canopy) can be described by the recollision probability p (Smolander & Stenberg, 2005) as:

$$s(\lambda) = i_0 \frac{\omega_L(\lambda) - p\omega_L(\lambda)}{1 - p\omega_L(\lambda)} \qquad \text{(Eq. 5)}$$

where ω_L is the leaf or needle scattering coefficient (also called the needle or leaf albedo) and i_0 is the canopy interceptance, defined here as the portion of incoming radiation (photons) hitting leaves or needles of the canopy.

The parameter p has been shown to be closely related to leaf area index but rather insensitive to solar zenith angle (Smolander & Stenberg, 2005). In other words, knowing the p value of a canopy, its scattering coefficient at any wavelength can be predicted from the leaf (or needle) scattering coefficient at the same wavelength (Knyazikhin et al. 1998a, b, Panferov et al. 2001, Smolander & Stenberg, 2003). In addition to leaf area index, the parameter p depends on the degree of clumping in the foliage distribution. So, for example, with the same leaf area index and phytoelement distribution and orientation in broadleaved and coniferous canopies, the coniferous canopies would have a higher p value due to their clumped shoot structure. Clumping at different scales (hierarchical levels) in the canopy is thus reflected by different p - LAI relationships.

Based on simulations in uniform leaf and shoot canopies, a simple exponential relationship between effective leaf area index and canopy p was established for the leaf canopy and a decomposition formula was shown to hold true for the shoot canopy i.e. the p for a shoot canopy can be calculated from shoot structural data (STAR) (Oker-Blom & Smolander, 1988). With this relationship between LAI_{eff} and p, and information on leaf or needle optical properties (ω_L) and shoot structure, we can calculate the scattering coefficient of the shoot canopy by only measuring leaf area index of the stand we are interested in (Eq. 5). It is now possible to present the bidirectional reflectance factor (BRF) of a forest as follows:

$$BRF = cgf(\theta_1)cgf(\theta_2)\rho_{ground} + f(\theta_1,\theta_2)i_0(\theta_2)\frac{\omega_L - p\omega_L}{1 - p\omega_L} \qquad \text{(Eq. 6)}$$

where θ_1 and θ_2 are the viewing and illumination zenith angles, *cgf* denotes the canopy gap fraction in the directions of view and illumination (Sun), ρ_{ground} is the BRF of the ground (which may also depend on θ_1 and θ_2, depending on the data available), f is the canopy scattering phase function, and $i_0(\theta_2)$ is canopy interceptance or the fraction of the incoming radiation interacting with the canopy. (Notice that $i_0(\theta_2)=1- cgf(\theta_2)$.) The canopy scattering phase function f is based on the simulations presented by Smolander and Stenberg (2005), and thus in this case is not a separate BRF model. The computation of the input p depends on whether the studied forest is broadleaved or coniferous.

Since this model was developed for studying the effect of including within-shoot scattering in a forest reflectance model and not for operational purposes, it is currently only a prototype. Therefore, several approximations were allowed. The model can be used only in off-solar viewing directions, since hotspot behavior has not yet been built in. It also does not include crown level clumping and the associated shading patterns that this can cause on the background, since the relationship of recollision probability and leaf area index used in this paper is based on Monte Carlo simulations done for uniform canopies (Smolander & Stenberg, 2005). Another simplification in the model is that the first term, i.e. the ground component in equation 6, does not include multiple interactions of photons between the tree layer and the understory layer, in other words photons that were reflected by the understory vegetation but did not escape the forest and were, for example, reflected back downwards by the above tree canopy. The reader should also note that the output of PARAS is BRFs (and not HDRFs as in the Kuusk-Nilson model) since in the current version of it applied here radiation can enter the canopy only from a narrow zenith angle band, not the whole upper hemisphere.

PARAS was applied to a large data set to simulate red and NIR reflectances of 800 Scots pine and Norway spruce plots located in central and southern Finland. The simulated reflectances were then compared to reflectances from Landsat 7 ETM images. First, simulations were carried out without the within-shoot correction. The differences between simulated and measured BRFs in the near-infra red wavelength were pronounced (RMSE ranging from 0.057 to 0.068), whereas in the red wavelength they were considerably smaller (RMSE ranging from 0.010 to 0.015). In the second phase of simulations, the within-shoot correction was applied to calculating the p of the canopies. Especially in the near infrared, the simulated and measured BRFs moved closer to each other (RMSE ranging from 0.040 to 0.049). Deciduous plots were clearly distinguished as the stands which had higher BRFs than the majority of other stands. The results of this study clearly indicated that a major improvement in simulating coniferous canopy reflectance in near-infrared can be achieved by simply accounting for the within-shoot scattering. Therefore, it can be claimed that the low NIR reflectance observed in coniferous areas is mainly due to within-shoot scattering. This result serves as a confirmation of the vague statements that have previously been made in attempts to qualitatively explain the difference in the spectral behavior of broadleaved and coniferous forests. In the red wavelength the effect of within-shoot scattering was not pronounced due to the high level of needle absorption in the red range. The model still requires development if it is, for example, to become invertible through a look-up table or to take into account also the macroscale grouping of tree crowns.

2.2. Spectral ground measurements

Most forest reflectance models require leaf or needle optical properties and ground layer (understory) spectral properties as their input. As additional input, in the case of geometric and hybrid models, a set of stand structural data is required to describe the trees. The routine stand data is usually relatively easy to obtain and faster to measure (and requires less sophisticated equipment) than measuring the spectral properties of phytoelements in the trees or understory. Therefore, it would be very useful to establish a data base of the optical properties of the most commonly needed forest components. A typical beginning for creating such a data base is to measure leaf or needle optical properties of the tree canopy species. Currently, several studies on spectra of needles different for different coniferous species exist (e.g. Panferov et al. 2001, Middleton et al. 1998, Williams, 1991, Daughtry et al. 1989). Scots pine (*Pinus sylvestris* L.) and Norway spruce (*Picea abies* (L.) Karst.), the two dominant tree species in Finland, have been covered in these studies (e.g. Panferov et al. 2001, Häme, 1991). However, even though very important, needle optical properties alone are not enough. Also other plant components such as bark, cones and understory need to be measured.

Even though needle optical properties measurements are challenging, it is more difficult to measure the spectra of a group of understory plants or soil due to, for example, spatial variability issues. It is either possible to measure the spectra of the vegetation in the nadir direction, as applicable for use with nadir-viewing satellite instruments, or alternatively, using a goniometer, to measure the bidirectional reflectance distribution functions which consume more time but perhaps serve a wider range of applications and theoretical modeling studies. In the case of boreal forests, a soil spectrum is not useful since the ground is covered by moss and a dense understory layer. In addition, the seasonal changes in boreal understory composition can be considerable and can also be expected to influence the spectral properties. Only a few studies on the spectra of the understory vegetation of boreal or sub-boreal forests have been carried out: the spectra of several understory species have been documented by Miller et al. (1997), Lang et al. (2002) and Kuusk et al. (2004), common lichens have been measured by Solheim et al. (2000), Rees et al. (2004), Kaasalainen and Rautiainen (2005), and mosses by e.g. Kushida et al. (2004) and Vogelman and Moss (1993). However, the angular distributions of reflectance (BRDFs) have not been studied for the common understory species. Thus, there is a clear need for this information. The focus here will be on the spectra and BRDFs of boreal understory species, since also in Studies I and III, ground spectra was a problematic input and it was clear that measurements on at least the most typical understory vegetation types are required for applying the forest reflectance models in the boreal region.

The BRDFs of common boreal understory species in natural growth form from a typical, dry Scots pine forest were measured as a part of this dissertation (Study IV). A newly developed field goniometer and an ASD Field Spec PRO FR spectrometer for the spectral range of 350 to 2350 nm were used. The species were blueberry (*Vaccinium myrtillus* L.), cowberry (*Vaccinium vitis-idaea* L.), crowberry (*Empetrum nigrum* L.), heather (*Calluna vulgaris* L.), a moss (*Dicranum polysetum* Sw.) and two reindeer lichens (*Cladina arbuscula* (Wallr.) Hale & W.C. Culb. and *Cladina rangiferina* (L.) Nyl.). Large differences between the strongly wavelength-dependent BRDFs of the species were found even though they all exhibited backscattering: lichens and heather the strongest and moss the weakest. Blueberry and cowberry were also noted to be relatively strong forward scatterers. Understory BRDF measurements are tedious and labor-intensive, and therefore the sample sizes of this study remained small. A wider range of structures of the same species should be measured in future experiments to enable error assessment and establishment of a reliable, average spectra data bank. Another challenge is extrapolating the measured BRDFs to other sun angles than those measured. Simple equations designed as a function of the viewing and illumination geometry to describe the directional reflectance properties of understory canopies (or bare soil) can be used for approximations (e.g. Walthall et al. 1985), but do not currently exist for our sample species and would need to be developed. However, formulating the equation can be difficult since plant species (optical properties), plant geometry and the density of the canopy may exhibit a wide range of values that the approximation should take into account.

The spectra measured in this dissertation are useful as input for forest reflectance models to characterize the spectral properties of boreal understory vegetation. However, the method for applying the spectra in the models is not simple because mixing of the various

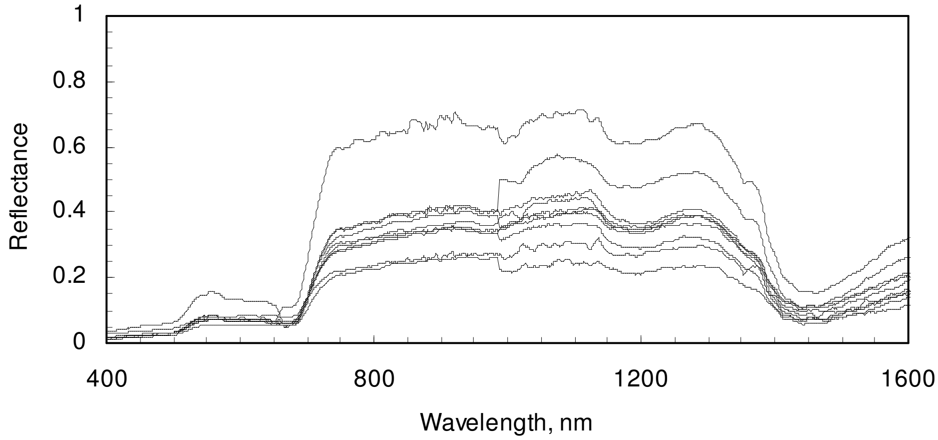

Figure 5. An example of a set of spectra of mixed, natural understory composition measured at several locations only a few centimeters apart from each other (Replotted data from data in Study IV).

understory species is not necessarily linear. This is due to the layered structure of understory species which cannot be taken into account when measuring the BRDFs of only single species (which represent a single layer). The layered structure can lead to, for example, shadowing effects which influence the contribution of the other layers on the BRDF of the target. It is also possible that the difference in spectra between two samples of the same species is as large as the difference between two samples of different species. The problem of spatial and temporal (in terms of illumination conditions) variation can be illustrated by looking at spectra of mixed understory vegetation i.e. results of several measurements that were made merely a few centimeters apart from each other over ground covered by a mixture of the study species (Fig. 5).

A possible limitation of Study IV is that the geometrical structure of the samples was not described in a detailed way - information which would possibly enable us to separate between the influence of structural and biochemical factors on the BRDF. However, for practical applications of forest reflectance models in, for example, mapping exercises, it would be very useful to be able to only use an ”average” spectrum for a given understory type.

The reflected signal of the understory needs to be separated from the signal of the overstory if we are interested in estimating variables related to the tree layer, e.g. leaf area index of the canopy. For traditional forestry purposes, different methods for estimating canopy cover have been developed (e.g. Williams et al. 2003, Jennings et al. 1999, Kuusipalo, 1985). However, using any allometric models for estimating canopy cover from basic stand inventory variables as input for forest reflectance models requires a good definition of canopy cover i.e. whether the canopy cover accounts only for the gaps between tree crowns or also for gaps within tree crowns. The role of gaps within coniferous tree crowns can be expected to be a significant factor in revealing the understory vegetation to nadir-viewing satellite or air-borne instruments (Fig. 6) (Study III).

Thus, to accompany the set of understory spectral data collected in this dissertation, canopy covers of seven Scots pine stands at the same site were assessed with two instruments in a detailed sampling scheme with 500 measurement points set as grid in a 0.20 hectare area

(Study V). For the measured stands, canopy cover (assuming solid crowns) varied from 48 to 79 % and single crown transmittance from 4 to 19 %. To my knowledge, the single crown transmittance values for Scots pine presented here, though for a small set of stands, are the first ones recorded from Finnish forests. Even though the data set was very small, it serves as an indicator for quantifying initial estimates of the role of understory as well as of the microscale grouping present in crowns.

Multiangular information on effective canopy cover, canopy cover which accounts for both between and within crown gaps, can be obtained using data from Studies II and V making several assumptions. If we assume that in viewing directions close to nadir single crown transmittance is relatively constant, and then combine this information with the crown shape model for Scots pine developed in Study II, it is possible to calculate effective canopy cover to a wider range of viewing angles – potentially useful in applications that require modeling or inverting stand reflectance in multiple directions (e.g. the POLDER instrument (Deschamps et al. 1994) or the MISR instrument (Diner et al. 1998)).

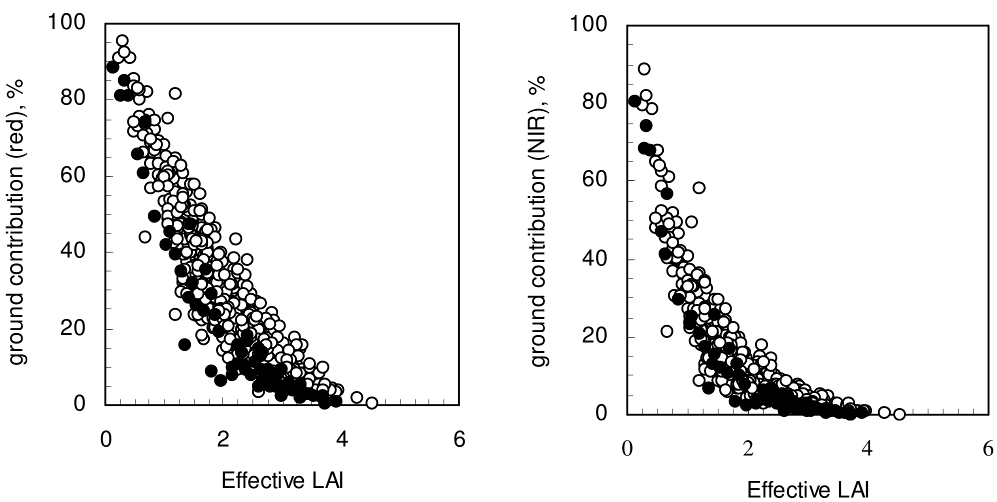

Figure 6. The contribution of understory to the total stand bidirectional reflectance factor (in percent) in the nadir-direction in red and NIR wavelengths for coniferous (white circles) and broadleaved (black circles) plots with the same effective leaf area index (Fig. 7 in Study III).

3. METHODS FOR LEAF AREA INDEX RETRIEVAL

3.1. Ground measurements

Reliable ground data are a prerequisite for developing and testing remote sensing methods for leaf area index retrieval. Several definitions of leaf area index can be found from literature and they often depend on the measurement technique that has been used. Originally, for flat leaves, leaf area index was defined as the total single-sided leaf area per unit ground surface area (Watson, 1947). Needles of the Finnish coniferous species are non-flat, typically hemicylindrical or rhomboid (e.g. Palmroth et al. 2002, Niinemets & Kull, 1995), and thus a more suitable definition for them is half the total interception area per unit ground area (Chen & Black, 1992, Lang, 1991). For comparing leaf area index values of coniferous and broadleaved canopies, a useful concept is that of effective leaf area index since, as mentioned previously, it assumes a random spatial distribution of leaves instead of the clumped pattern that is observed in reality.

In situ leaf area index measurements can be made using direct or indirect methods. Direct methods, for example litter traps or destructive techniques, are accurate, but time-consuming and not suited for large areas or continuous monitoring purposes. However, they are important as calibration methods for indirect measurements (Jonckheere et al. 2004). Indirect methods derive leaf area index from other, easily measurable variables and can thus be used for larger areas than direct methods. Examples of indirect methods are allometric equations (often based on the pipe model theory (Shinozaki et al. 1964)), the point quadrat method (Wilson, 1960) or optical methods. Indirect optical methods for leaf area index estimation have become popular as commercial instruments (Li-Cor LAI-2000 Plant Canopy Analyzer, TRAC, DEMON, hemispherical photography) and algorithms related to them have been developed. The basic principle launching the development of the optical methods was using the inversion of the theoretical gap frequency formula for horizontally homogeneous plant canopies i.e. applying Beer's law for radiation transmitted (penetrating) through a canopy.

Applying the optical leaf area index measurement techniques in coniferous forests is problematic. For example, the LAI-2000 Plant Canopy Analyzer has been reported to underestimate leaf area index in coniferous stands (Stenberg et al. 2003, Nilson, 1999, Deblonde et al. 1994, Stenberg et al. 1994, Smith et al. 1993, Gower & Norman, 1991). This result is not a surprise, since the optical instruments are based on the principle of inverting canopy gap fraction values (i.e. canopy transmittances) for a canopy where leaves are randomly distributed. Coniferous canopies are non-random due to their high level of clumping at various levels (e.g. Oker-Blom et al. 1991) and thus applying a model assuming random distribution will lead to inaccurate results (Stenberg, 1996, Stenberg et al. 1994). As the clumping phenomenon has been widely acknowledged as a problem (e.g. Nilson, 1999, Kucharik et al. 1998, Stenberg 1996, Chen, 1996), various methods have been suggested for correcting the leaf area index or gap fraction values measured by the optical sensors to obtain "true" leaf area index values. These correction methods can be divided roughly into two groups: (1) methods which assume a quasilinear relationship between the optically measured leaf area index and the true leaf area index (e.g. Kucharik et al. 1998, Stenberg, 1996, Chen, 1996) and (2) methods which allow a non-linear relationship between the measured and true values and thus use a canopy radiation model for performing the correction (Nilson, 1999). Currently, a general problem with the correction methods is that they are not universally applicable as they typically require relatively detailed information on species or stand characteristics (Weiss et al. 2004).

The LAI-2000 Plant Canopy Analyzer was used to measure the ground-comparison leaf area index needed for the remote sensing studies of this dissertation (Studies III, VII, VIII). The instrument has an optical sensor which consists of five detectors arranged in concentric rings measuring radiation between 320 and 490 nm, where scattering from leaves is minimal. A close to hemispherical image of the above canopy is projected onto the rings. Canopy gap fraction in each of the five different zenith angle bands is then calculated as the mean ratio of below- and above-canopy readings by the corresponding detector rings. Finally, effective leaf area index is calculated from canopy gap fractions based on Beer's law.

In Study VII, a comparison of the optical leaf area index estimates was made to allometric leaf area indices derived using a needle biomass model developed in Sweden for Scots pine and Norway spruce (Marklund, 1988) coupled with corresponding specific needle area values (Palmroth et al. 2002, Smolander & Stenberg, 1996). A canopy radiation model (Nilson, 1999) was used to correct the values measured by the LAI-2000 Plant Canopy Analyzer for clumping. The leaf area index values obtained both with the allometric equations and the canopy radiation model were larger than the ones measured with the LAI-2000 instrument (Fig. 7), a result which is in agreement also with the previous

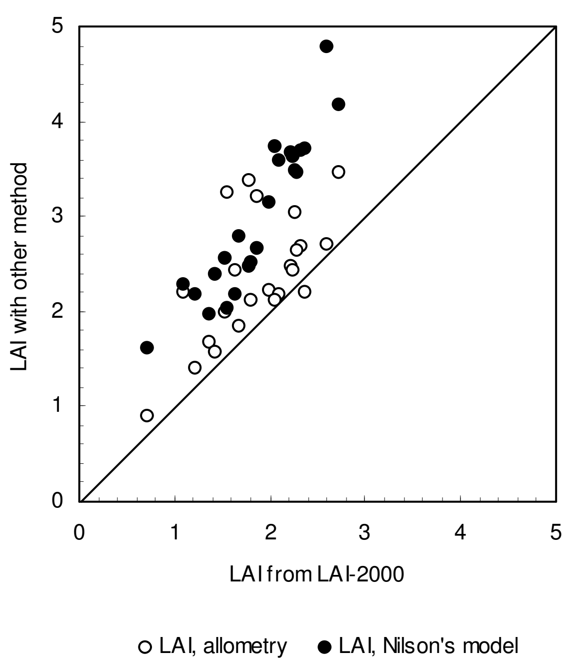

Figure 7. An example of ground-comparison leaf area index values for pure Scots pine stands obtained with the LAI-2000 instrument and (1) allometric equations by Marklund (1988) (r = 0.64) and (2) a canopy radiation model by Nilson (1999) (r = 0.92). The correlation coefficient (r) of allometric leaf area index (1) and leaf area index with Nilson's model (2) is 0.43. (Replotted data from Study VII.)

studies referenced earlier. Even though the focus of this dissertation is not on developing ground estimation techniques for leaf area index – a research field of its own – the information of the relationship of the different ground-comparison leaf area index values is valuable for interpreting remote sensing results.

3.2. Inversion of forest reflectance models

Inversion of forest reflectance models is an indirect method for obtaining leaf area index estimates. To understand the use of these models in remote sensing studies we need to define two concepts, the direct problem and the inverse problem. The direct or the forward problem in radiative transfer and remote sensing studies is the mathematical description of the relationship between a model parameterization of vegetation and stand reflectance. When remote sensing data (e.g. reflectances) are available and we want to obtain a given vegetation variable using the model, the process is called the inverse problem. The direct problem can be expressed with a simplified functional relation (R) as:

$$S = R\,(C, L) \qquad \text{(Eq. 7)}$$

where S is the measured spectral signature, and C are known ground-comparison parameters and L is the unknown parameter to be estimated (e.g. leaf area index). The inverse problem is to solve L when S is available. It is thus clear that if the forward problem cannot be solved, inversion of the model is not possible either. The stability of the direct problem (the sensitivity of the simulated reflectances to variations in input) affects the inversion results. Inversion of remote sensing data for biophysical attributes is also well-known to be an ill-posed problem: many parameterizations of the reflectance model may correspond to the same measured reflectance(s) and there are uncertainties both in the measured spectra and the model (Combal et al. 2000). In other words, there is no unique solution and the obtained solutions may be unstable.

Three general groups of methods for inverting reflectance models have been listed (Kimes et al. 2000): numerical optimization methods (e.g. Kuusk & Nilson, 2000, Jacquemoud et al. 1995a), look-up table (LUT) methods (e.g. Weiss et al. 2000, Knyazikhin et al. 1998b) and neural nets (e.g. Baret et al. 1995, Weiss & Baret, 1999). Numerical optimization methods are currently perhaps the most widely used tools in canopy reflectance model inversion. This can be explained by the relatively rapid inversion of non-analytical functions they are able to perform. Look-up table based inversion operates through a data base of pre-calculated stand reflectances under many viewing and illumination scenarios, wavelengths and vegetation or site types. A best-fit solution is searched from the data base, and thus basically any canopy reflectance model that can be run in the forward mode can be used with the look-up table (e.g. Knyazikhin et al. 1998b) – an obvious strength of this approach. However, creating the LUT can be complicated and, if carefully done, requires an extensive set of reliable field measurements. The third group of inversion methods, neural networks, has recently shown computationally efficient inversion results by decreasing inversion time and taking into account radiometric information for neighboring pixels (e.g. Atzberger, 2004).

A key question in inverting forest reflectance models is naturally how we can assess the quality of the parameters we retrieve through inversion. A typical method is to compare them to ground measurements (if they exist). This should work well when we have reflectance data measured right above the canopy i.e. problems related to the atmospheric corrections or geolocation do not need to be accounted for. Comparing inversion results with results from other models is also a possibility even though it does not reveal anything about the ground-comparison values.

In this dissertation, the Kuusk-Nilson forest reflectance model was inverted for retrieval of leaf area index over coniferous sites. The inversion of the model is based on a numerical optimization method (Powell's method) where a merit function is minimized to obtain the best fit between simulated and measured reflectances. The range of possible solutions is limited by giving an initial expert guess and its uncertainty in the input file. A recommendation by the model developers is to restrict the number of inverted parameters as the number of model parameters is rather large. In this case, however, this was not a problem since inversion was performed only for leaf area index. For the inversion, an initial guess (expert estimate) of leaf area index together with its uncertainty is needed. The inversion yields a value for the leaf area index, which minimizes the merit function F, defined as:

$$F = \sum_{i=1}^{2} \frac{\left[R_{\lambda i}^{simul}(LAI) - R_{\lambda i}^{meas}\right]^2}{\varepsilon_{\lambda i}^2} + \left(\frac{LAI - LAI_e}{\Delta LAI}\right)^2 \qquad \text{(Eq. 8)}$$

where $R_{\lambda i}^{simul}$ and $R_{\lambda i}^{meas}$ are the reflectance factors at the wavelengths λ_i simulated and determined from the Landsat ETM image, respectively; and ε_i are the uncertainties of the measured reflectance factors. In the second term of the merit function, LAI_e is the expert estimate (or initial estimate) of leaf area index and ΔLAI is the preset uncertainty of the estimate. Instead of single band reflectances it could also be possible to perform the inversion through combinations of spectral bands i.e. spectral vegetation indices (described in Section 3.3. Spectral vegetation indices). However, in this study inversion using these indices was not tested.

The Kuusk-Nilson model was inverted using data from two Scots pine dominated test areas. Study VI concentrated on estimating leaf area index over an area using a priori knowledge of stand borders to average the reflectances for a stand before performing the inversion of a SPOT HRVIR1 image using the spectral bands B2 (red, 610-680 nm), B3 (NIR 780-890 nm) and B3 (MIR, 1580-1750 nm). Study VII, on the other hand, focused on understanding the effect the initial expert guess has on the inverted leaf area index value. Here only pure Scots pine stands were used for the inversion together with the ETM3 (red, 630-690 nm) and ETM4 (NIR, 775-900 nm) bands of a Landsat 7 ETM image.

Results from both studies showed that simulated reflectances were in general slightly larger than the reflectances measured by the satellite instruments. It is possible that this could be explained by the within-shoot scattering parameterization which is missing in the Kuusk-Nilson model - the scattering function of leaves in the current model version could be replaced by the scattering phase function of shoots when doing the simulations for coniferous forests. Accounting for this phenomenon could decrease the reflectances, as observed with the PARAS model in Study III. Similar results of too high reflectances for coniferous stands have been reported also previously (Kuusk & Nilson, 2001). Other possible reasons are problems related to quantifying canopy cover or transmittance in the inversion, since it was not measured and was generated based on allometric equations from the routine forestry data.

Study VI served as a pilot study for estimating leaf area index in Finnish forests by running a physically based forest reflectance model through an operational forest management data base and a SPOT HRVIR1 image. Inversion of the reflectance model was done twice: first using as simultaneous input three wavelength bands (red, NIR and MIR), then only the red and NIR bands. The aim was to observe whether including the MIR band in the inversion would improve the inverted leaf area index estimates or if using only the red and NIR bands would result in the same reliability of inverted values. The motivation for examining the influence of the MIR band was results from several recent studies from the boreal zone which suggest that the pronounced understory effect could be minimized by the inclusion of the MIR band in spectral vegetation indices. The leaf area index values inverted by the model were slightly larger than the ground-truth leaf area index values, and only a minor improvement in the inverted LAI estimates was observed after the inclusion of the MIR band in reflectance model inversion.

In addition, as the inversion of the model requires as input an initial estimate of leaf area index and the uncertainty of it, it was noted that when the uncertainty of the initial leaf area index guess increased, correlation between the retrieved and initial leaf area index values decreased (Study VII). The results in general indicated that to be able to use this type of inversion technique relatively detailed information should be available or possible to be generated (based on other models) for the studied stands. This may pose problems for practical mapping applications.

Another problematic issue in the two inversion studies was defining the scale of the area to be used for inversion. Inversion of reflectance models can naturally be performed pixel-by-pixel (as in Study VII), but this can be expected to lead to unreliable results due to, for example, geolocation problems or adjacent pixel influences. Using a priori ground-comparison information (as in Study VI) or pre-classification of the image for averaging the reflectances over larger areas is a better option. Leaf area index estimates are rarely desired for 20 m x 20 m or 30 m x 30 m areas in environmental monitoring, and thus scaling over more extensive areas is justified also by application purposes, not only reasons related to interpretation techniques. However, as the scaling issue and extrapolation functions are a research fields on their own, this dissertation does not touch on the topic but concentrates on the basic phenomenon behind the spectral signatures. Extrapolation and related scaling issues remains a topic for future research.

3.3. Spectral vegetation indices

Based on the amount of published studies to date, the dominant method for interpreting vegetation biophysical properties from optical satellite data is through spectral vegetation indices. Spectral vegetation indices (SVIs) are combinations of reflectances measured in two or more spectral bands and used to retrieve various biophysical variables, most commonly leaf area index. They can be considered a very simplified type of reflectance models with some physically explainable principles behind them. Their popularity lies in the fact that they require very little expertise of the physical principles of remote sensing or modeling, and are computationally fast to process. The indices aim at estimating canopy biophysical properties through enhancing the spectral contribution of vegetation while minimizing the contribution of the underlying soil or understory vegetation (e.g. Verstraete & Pinty, 1996, Huete, 1989).

Many indices have been proposed specifically for leaf area index estimation (e.g. Table 1). These indices typically involve reflectances from red and NIR spectral bands, as in the commonly used NDVI (normalized difference vegetation index) or SR (simple ratio) which are based on the sudden increase in leaf reflectance observed at the red edge. Relatively strong, site specific relationships between these indices have been found in many studies for different vegetation types (e.g. Eklundh et al. 2001, Turner et al. 1999, Nilson et al. 1999, Chen et al. 1999, White et al. 1997, Jakubauskas & Price, 1997, Law & Waring, 1994, Nemani et al. 1993, Spanner et al. 1990). The use of NDVI or other indices for leaf area index estimation at regional scales thus would require classification into vegetation types or land cover classes with different, class specific SVI-LAI relationships (e.g. Myneni et al. 1997b). In addition, NDVI or any other index chosen for mapping should be sufficiently sensitive to changes in leaf area index throughout its natural range. However, a problem documented already a long time ago with SVIs such as the NDVI is that they tend to saturate at high levels of leaf area index (e.g. Sellers, 1985). In addition, recently problems related to the use of NDVI in the boreal zone have been reported (Eklundh et al. 2001, Nilson et al. 1999, Häme et al. 1997, Chen & Cihlar, 1996). These studies have indicated that NDVI is not dynamic enough to be suitable for leaf area index estimation in coniferous regions as the range of NDVI of boreal coniferous forests is typically narrow, and the index reaches nearly saturated values already at moderate values of leaf area index. This is probably mainly due to the complex green understory which results in a non-contrasting background reflectance in the visible part of the spectra (Nilson & Kuusk, 2002, Myneni et al. 1997b, Nilson & Peterson, 1994). Therefore, an index which is able to take into account the effect of the understory would be more optimal for leaf area index retrieval in coniferous forests.

The importance of including water absorbing MIR bands as additional sources of information has been acknowledged already nearly two decades ago (Baret et al. 1988), but only recently included as an improvement for leaf area index estimation for coniferous

Table 1. Applied spectral vegetation indices. (ρ_i is the reflectance at band *i*.)

Index name	**Abbr.**	**Formula**	**Reference for description**
Normalized difference vegetation index	NDVI	$\frac{\rho_{NIR} - \rho_{red}}{\rho_{NIR} + \rho_{red}}$	Rouse et al. 1974
Simple ratio	SR	$\frac{\rho_{NIR}}{\rho_{red}}$	Jordan, 1969
Reduced simple ratio	RSR	$\frac{\rho_{NIR}}{\rho_{red}} \cdot \left(\frac{\rho_{MIR,\max} - \rho_{MIR}}{\rho_{MIR,\max} - \rho_{MIR,\min}} \right)$	Brown et al. 2000
Moisture stress index	MSI	$\frac{\rho_{MIR}}{\rho_{NIR}}$	Vogelmann, 1990

forests in the reduced simple ratio index (RSR) (e.g. Brown et al. 2000). Results from studies conducted in Canada have shown that leaf area index of coniferous (and deciduous) forests is better estimated with the RSR than with the SR which is based only on red and NIR reflectances (Chen et al. 2002, Brown et al. 2000). A study carried out in Sweden (Eklundh et al. 2003) also supported the use of RSR for coniferous forests where it performed better than in deciduous forests.

In the studies of this dissertation, four spectral vegetation indices, NDVI, SR, RSR and MSI were tested for mapping leaf area index over three Scots pine and Norway spruce dominated test areas (Studies VI, VII and VIII). The general result of these studies emphasized the insensitivity of NDVI to leaf area index in both simulation studies (Study VII) and empirical studies (Studies VI, VII, VIII). The general performance of SR and MSI was comparable to that of NDVI in terms of insensitivity. RSR, on the contrary, performed remarkably well: variation in leaf area index over the sites was captured well by the LAI-RSR regression in Study VIII which was primarily dedicated to investigating the use of spectral vegetation indices. Estimated values of leaf area index using RSR agreed well with the measured ones, and even rather small scale variation in leaf area index was captured. The performance of RSR was weaker at plots around which leaf area index values were relatively constant but the reflectances heterogeneous due to non-vegetation component or disturbances (e.g. logging roads, rocks, large ditches). It is reasonable to believe that such large deviations due to the non-vegetation components will usually be of small scale and influence only the satellite image (RSR) based leaf area index estimate of approximately one or two stands. This is an advantage of using e.g. the Landsat ETM or SPOT HRVIR1 pixel size. However, RSR did not perform as well in Study VI where pixel reflectances were averaged over whole stands (i.e. in Study VIII reflectances were averaged over a smaller area around the plot center). In Study VI, RSR exhibited the widest and NDVI the narrowest range of values as a function of leaf area index, suggesting again that RSR is the most dynamic of the tested indices for coniferous forests. This can be considered a clear advantage in leaf area index estimation.

4. GENERAL RESULTS AND DISCUSSION

The characteristic signatures of coniferous forests have often been vaguely mentioned in published articles or passed by in discussions at conferences even though several optical remote sensing studies involving modeling of biophysical variables exist from the boreal zone (e.g. Eklundh et al. 2003, Gemmell et al. 2002, Eklundh et al. 2001, Chen et al. 2002, 1999, Gemmell & Varjo 1999, Gemmell, 1999, Nilson et al. 1999, Strandström 1999, Chen & Cihlar, 1996, Nilson & Peterson, 1994). A systematic, thorough study or sequence of studies of the basic phenomena behind the signatures has not been presented and thus the literature in this field is lacking of some fundamental principles. Besides theory development, this also has had an impact on both the basic teaching, and application and mapping results obtained from the interpretation of optical images. The purpose of this dissertation was to provide new insights to how the spectral signature of a boreal coniferous stand is formed. The role of the first part of the dissertation was to examine macro- and microscale grouping influencing the spectral signature of boreal coniferous forests and of the second part to concentrate on leaf area index retrieval.

To begin with, the Kuusk-Nilson model was used to study the influence of one level of macroscale grouping, caused by the distinct tree crown shape of conifers, on total stand reflectance. This study served both the purposes of basic theory development and identification of forest attributes which should be acknowledged in the application of physically based models to interpret satellite images for mapping. Previously, it has been noted (Eklundh & Harrie, 2000, Gerard & North, 1997) that crown shape affects the total directional reflectance from a stand, but to my knowledge the size of the scattering components in boreal coniferous forests has not been looked into in detail before this dissertation. Simulations in Study I with the Kuusk-Nilson forest reflectance model provided some understanding to the macroscale grouping present in coniferous forests. The results showed that in a stand with a higher canopy closure single scattering from tree crowns is responsible for the reflectance difference between stands with different crown shapes. On the other hand, in a stand with a smaller canopy closure the single scattering from ground dominates stand reflectance. This can be generalized to state that when canopy closure is high, little of the ground is sunlit irrespective of crown shape. Therefore, reflectance from the tree crown layer will have a greater influence than that from the ground layer on stand reflectance. According to the results of the study, crown shape and volume are the main factors influencing the magnitude of the single scattering reflectance from crowns and ground when other parameters are constant. In other words, when crown volume is increased and leaf area density decreased, crown projection area as well as the total sunlit area (and thus reflectance) increase. Crown shape determines partly the spatial distribution of sunlit foliage in the canopy and thus also the probability that radiation reflected from the sunlit crown will reach the sensor. The more radiation is intercepted (and reflected) by the tree crowns, the less reaches (and can be reflected from) the ground. Differences in stand reflectance will therefore be smaller than the differences in the component for single scattering from the tree layer for different crown shapes. The results confirmed that crown size and shape indeed has an influence on stand reflectance – the smaller the crown volume, the lower the canopy reflectance -, and thus its role in the inversion of reflectance models requires consideration and further study, especially if the same reflectance value yields two very different parameter values (for instance leaf area index) as a result of different crown shape assumptions. A reservation to keep in mind when applying the results of this study is that satellite instruments measure in-orbit radiances of vegetation through the atmosphere, and therefore the obtained surface reflectances need to be corrected for, for example, atmospheric and topographic effects i.e. uncertainties will be present in the measured reflectances. In other words, it is unclear whether or not the effect of crown shape can be observed with the current level of preprocessing of the satellite data. Nevertheless, this does not diminish the importance of understanding how the spectral signal is influenced by crown shape and the scattering volume defined by it.

The second clumping feature of coniferous forests to be examined was the microscale grouping, grouping of needles into shoots, and how this affects the spectral signature of coniferous forests. The basic phenomenon captured by including shoot scale clumping is the multiple scattering of photons within shoots that is not included in the previously used Kuusk-Nilson model. Results from applying the new PARAS model to empirical data (Study III) indicated that the low NIR reflectances widely observed in coniferous areas can largely be explained simply by accounting for within-shoot scattering. In the red wavelength range the differences were not pronounced and were related to the low level of multiple scattering and high level of absorption present in the red range. However, even though within-shoot scattering seems to explain a large part of the difference between broadleaved and coniferous forests, also other, possibly minor, explanations (e.g. differences in absorption spectra of needles, leaves and woody material) for the optical differences should be acknowledged as they were not included in this study.

In addition to serving as a tool for understanding the effect of microscale grouping, the PARAS model could be developed into an operational version with further work. This would require exploring the effect of clumping at larger hierarchical scales in the canopy (e.g. crown shape as in Study I) on the p – LAI relationships, and including it in the model if necessary. After modifications and establishment of a spectral data bank of the properties of boreal forests the PARAS model could have an operational version functioning through a look-up table. In the case of Finnish forests, the leaf area index range that will be retrieved also falls into the range where p is more sensitive to leaf area index (i.e. leaf area index under 4), further supporting the use of this parameterization. To proceed in this activity, an extensive empirical data bank needs to be collected for understory BRDF (e.g. Study IV), canopy structure (e.g. Study II), gap fraction (e.g. Study V) and leaf area index measurements which can then serve as the basis for a look-up table. The main advantage of the model that can be seen currently is that it would require minimal input to describe the reflectance of a canopy. However, including more profound aspects of reflectance modeling, such as the hot-spot effect, would still require extensive work. On the other hand, it is possible to use or incorporate photon recollision probability into other canopy reflectance models besides PARAS. Nevertheless, it remains important to be able to see the performance of the so-called p-approach alone (as in the PARAS model) without other influencing details and stand structure which are present in, for example, the Kuusk-Nilson model.

Naturally, before operational applications, also the relationship of recollision probability p and leaf area index should be derived empirically. The recollision probability can be calculated from measurements of the up- and downwelling fluxes below and above a given canopy, leaf optical properties and understory reflectances. The measurements should be carried out for a range of stands with different leaf area index values but same species composition (i.e. similar geometric structure). However, currently development of the methodology has already been started with a data set for Norway spruce stands in northern

Sweden, but it is still under refinement. When examining the empirical *p*-LAI relationship, possible sensitivity of the recollision probability to changes in needle reflectance and transmittance should also be studied. If the recollision probability turns out to be very sensitive to needle albedo (or the quality of the needle albedo data!), in other words, if the relationship of canopy leaf area index and recollision probability is highly dependent on needle optical properties, the whole approach becomes questionable and will not be applicable. In other words, even though the recollision probability can be calculated from empirical data, needle optical properties (as can be seen from Eq. 5) can influence it considerably.

With the help of the results obtained in the first part of the dissertation, it is possible to outline how to model grouping in physically based models for coniferous stands. It seems that in terms of multiple scattering, total crown volume (i.e. canopy volume available for scattering to occur in) is probably more important than modeling the exact crown shape itself. However, when considering the first interactions of photons in the canopy, modeling crown shape relatively correctly could be of significance. A useful and easily applicable approximation would be calculating canopy volume (obtained from stand density and an approximate allometry-based crown shape model such as presented in Study II) and including the multiple scattering component through a recollision probability function. This would be a coarse compromise between the two modeling approaches used in Studies I and III, and would also require less a priori input on the important grouping phenomena. In addition, together, separately or as a hybrid version, these models could be combined with the ground measurements made in this dissertation (Studies II, IV, V) and future field work to create a spectral data bank first on Finnish or North European forests and then, hopefully, boreal forests in general. Properties measured for the data bank, in other words, input used for any reflectance model, should be measurable biophysical variables that can be readily understood to describe plant or stand properties. Such a spectral data base linking structural and optical properties of forests would be a very useful result of basic research (field work and modeling) that could then be widely applied in both statistical and physically based remote sensing techniques. The relationship of satellite images and forest structure would be based on a more quantitative than qualitative understanding. In remote sensing applications, a decrease in computing time can be used as an argument for simplifications in the model. However, a balance between the simplifications and goal of the modeling exercise should be found – a simple model for operational mapping, a more detailed model as an educational tool to explain radiative transfer and structural properties influencing it.

In the second, application part of the dissertation, leaf area index retrieval methods were tested with spectral vegetation indices and inversion of a forest reflectance model. A general problem of applying global leaf area index retrieval models in Northern Europe, and especially in Finland, is that the forested areas are typically fragmented, for instance due to high level of private land-ownership, and the moderate and coarse resolution solutions are thus not accurate enough if relatively detailed leaf area index mapping is desired – which, of course, depends on the goal of the activity. High resolution images together with simple physical or semi-physical models developed for local vegetation types would in general provide more reliable information which could also be used for vegetation monitoring and societal purposes. Thus, such a methodology developed in Finland could well be applicable also in other corresponding boreal areas with similar vegetation composition.

Leaf area index estimates obtained by inverting the model over two test areas in central and southeastern Finland (Study VI, VII) showed that the allometric estimates of leaf area index were smaller than the inverted values. A possible reason for the inverted leaf area index values being higher than the allometric ones is that the understory vegetation was parameterized unsuccessfully and the model retrieved also partly the understory leaf area index, not only the canopy leaf area index. In this dissertation, the contribution of understory reflectance to coniferous stand reflectance was reported to be high and to range from 0 to 95 % for effective leaf area index values below 5 (Study III). Measurements in Scots pine stands have indicated that single crown transmittances can be from 5 to 20 % (Study V) - a fact that places even more emphasis on the role of the understory in optical image interpretation in boreal forests. In this case, the understory reflectances were set constant for all plots based on previously reported measurements made at the same study area (Study IV). As suggested by Kuusk and others (2004), a solution could be predicting the understory reflectances from stand data (i.e. stand structure or site type).

Nevertheless, an aspect that should be remembered in assessing how successful the inversion was is that the ground-comparison leaf area index was based on an allometric model which used the stand inventory data as its input. Thus the ground-comparison estimates for leaf area index were not measured and contain the errors which are already present in the stand data. Assessing the errors present in any allometric leaf area index estimates is very difficult. Even if optical methods (e.g. LAI-2000 Plant Canopy Analyzer) are used, they provide the so-called effective leaf area index which would need to be corrected by clumping factors in order to obtain the ‘true’ leaf area index. The assessment of errors in leaf area index values obtained with any methods (besides destructive sampling which naturally is not suitable for monitoring purposes) is typically based on the review of other related literature or comparison of different measurement techniques. Nevertheless, the allometric model by Marklund (1988) used in this dissertation has been shown to be the most representative of models available for biomass calculations in Scandinavian forests and especially in regularly managed stands dominated by Scots pine in Finland (Kärkkäinen, 2005). Marklund’s model is widely used in Scandinavia and advantages of the model are that the data used for developing it covers wide diameter and site fertility ranges and was collected to be regionally representative (Kärkkäinen, 2005, Marklund, 1988). Nevertheless, a difficult issue is that we do not have strong evidence of exactly how accurate the models are, and, whether remote sensing could actually produce more reliable results. However, in a practical application, measured leaf area index values would not be available and the estimates would often have to be based on allometric models as in this dissertation. An interesting study would be assessing the use of different allometric models in generating the input for a forest reflectance model. Unfortunately, a general limiting factor is that reliable and simple allometric models are scarce, and since they are species-specific, they are available only for a few commonly studied species and regions.

In addition to physical reflectance models, another approach to leaf area index estimation from satellite data are spectral vegetation indices. Physically based theoretical models have the advantage over empirical regression models that they are, at least in principle, less site-specific. Application of such models, however, is often limited by the requirements of fairly large homogeneous areas and/or additional unknown input data, and use of spectral vegetation indices is often the only option. On the other hand, even though spectral vegetation indices are considered to diminish to a certain extent the background effect in canopy leaf area index estimation, the fact that the relative contributions of the ground and tree layer components differ along with sensor and sun angles should be recognized. In practice, this means that the derived regressions are sensor-dependent in two ways: they depend on solar angle and band width. In other words, a regression developed for one sensor may not be directly applicable, at least without further study, to another instrument. Nevertheless, the use of spectral vegetation indices for leaf area index mapping is tempting due to the fact that no before hand information is required from the region and that the computation time required is short.

For the coniferous study sites presented here, leaf area index mapping became more successful when a MIR band was included in the index, possibly explained by the sensitivity of MIR to the water content (and thus indirectly the amount) of needles (Study VIII). Previously, Brown et al. (2000) have noted that the inclusion of MIR in the RSR normalizes for background reflectance and thus performs well. The results of the studies presented here do not offer clear support (nor contradiction) to their results, possibly due to the narrower range of understory vegetation types. The results from both the simulation studies (Study VII) and empirical regression studies (Studies VI, VII and VIII) supported abandoning the widely used NDVI as a method for mapping leaf area index in the coniferous region and emphasized turning to other, more dynamic indices such as the RSR. The performance of RSR in Study VIII was remarkably good: variation in leaf area index over the sites was captured well by the LAI-RSR regression ($r^2 = 0.75$) and the small scale trouble areas (large deviations between measured and predicted leaf area index) could be identified to contain a disturbance, an abnormality from the basic, "pure" forest structure. Even in Study VI, where the SVIs did not perform well, RSR was still the most dynamic index. It is reasonable to say on the basis of our results and previous studies that exploring the applicability of different spectral vegetation indices alongside developing physical reflectance models remains an important field of research.

A problem common to application of either the forest reflectance model or spectral vegetation indices was the relatively small pixel size of the used images (20 m x 20 m in SPOT HRVIR1, 30 m x 30 m in Landsat 7 ETM) as adjacent pixels (and the tree crowns in them) could have influenced each other when they extend across the pixel borders. Collaboration with image segmentation experts would possibly improve the results and lead to more refined mapping methodologies. Geolocation and scaling, extrapolating transfer functions, image preprocessing and atmospheric corrections are examples of the many issues that need to be assessed before any operational use of remote sensing methods. As the primary purpose of this dissertation is on the physical phenomena in the canopy, these topics clearly fall outside the scope of this specific presentation, but should be addressed in future work.

What kind of recommendations can be made for leaf area index retrieval methods after these studies? How well can we estimate leaf area index given the limited models and data available today? The results indicate that whether using a forest reflectance model or a spectral vegetation index, a NIR and a MIR band from the satellite image should be included in the retrieval method and the currently widely used NDVI should not be applied in coniferous regions. The choice of the retrieval method itself should be made on the data available. If only an image is available and there is no predefined, reliable look-up table to run a physically based model through, spectral vegetation indices are a feasible choice. However, it seems that a limitation of the spectral vegetation indices may be problems related to their parameterization for different biomes. In the case physically based models are chosen, the model should be such that its input data set or look-up table is easily acquirable. Currently, even though a large number of models exists, the input required for them is often not readily accessible (or has never even been measured or otherwise documented). In regions where basic forest mensuration data are available, a reflectance model using the data set as input could be a justified choice. However, models using the more traditional inversion algorithms are computationally expensive. If a look-up table is available and has been built so that different forest reflectance models can use it, the look-up table based approach is also practicable and faster even though it requires predefining of various biophysical properties or relationships. On the other hand, if a reliable (and updated) stand data set collected for another purpose is available, it is probably more practical to calculate leaf area index directly from that data using allometric equations than to use remote sensing through a physically based reflectance model which already by itself requires stand data as input (e.g. the Kuusk-Nilson model). Nevertheless, there always remains the issue of reliability versus practicality – it is well possible that the remotely sensed leaf area index values would be more reliable as well as frequently updated and available due to the dense temporal sampling of remotely sensed images. A satellite image is also inexpensive compared to manual labor.

A current problem for both spectral vegetation indices and physically based model approaches is the scaling issue: measured spectral signals depend on resolution i.e. pixel size. On the other hand, this can also be turned the other way around. Combining multiresolution and multitemporal data sets might be an interesting option if the statistical problems related to integrating the data sets can be solved. Multitemporal data sets are tempting in optical remote sensing of canopy biophysical properties also because obtaining cloud free images can be difficult.

Improving the current leaf area index retrieval methods and developing new ones will require carrying out extensive field campaigns for testing and validating the methods. The field campaigns should be designed systematically so that a spectral data base could be collected at the same time. Such a data base would serve both various application results (remote sensing of any forest or vegetation variables) and teaching of the basic physical principles of remote sensing. The data base should include routine stand data, optical properties of tree components (needles, leaves and bark), understory vegetation and whenever possible, either modeled or measured reflectances of the whole stand. Since the reflectances have a seasonal course (e.g. Nilson & Peterson, 1994), an ideal data base would also include measurements or some other indication of how the optical and geometrical properties of the stand change seasonally. The spectral changes of under- and overstory vegetation are not synchronized during the boreal summer which poses a serious challenge to remote sensing. It is thus obvious that establishing such a data bank is laborious. Besides measurements, another approach to compiling a spectral data bank would be through extensive runs of forest reflectance models which have demonstrated their ability to mimic the spectral behavior of the stands sufficiently well. The models could mainly be used to generate stand reflectances from the routinely measured data. On the other hand, inversion of forest reflectance models could then also be seen in some cases as a means of assessing or updating possibly erroneous stand data in data banks, assuming the satellite data to be more ‘correct’ than the approximated stand data. When considering the coniferous forests in Fennoscandia, a clear advantage to other boreal regions is the fact that our range of tree species is very narrow (e.g. when compared to Canada). Thus, establishing a simple structural and optical data bank for this region will require less field work and is achievable faster. Only a perfectly functioning forest reflectance model, which could totally mimic the spectral behavior of a forest, could remove the need for an extensive spectral data bank. However, it is very probable that such as model will require a spectral data base for its development and validation.

Finally, it is time to ask a question – how useful is it to map leaf area index with remotely sensed data? The answer is not simple. If we approach this question from a domestic perspective in Finland, it must be admitted that the state of our forests is already well documented in rather sophisticated inventory data bases, even though not commonly accessible. On the other hand, combining these data bases and remotely sensed leaf area index values would probably result in one of the world's most prominent leaf area index maps. If, in the future, process-based stand growth models are routinely implemented in these data bases to quantify stand growth, the importance of having leaf area index estimates in the same data base (to be used as input for the models) will considerably increase. Also the dense temporal sampling of the forested areas available through remote sensing is of high significance – both labor costs and time can be saved already at national scale when compared to manual methods. The international perspective to leaf area index mapping is even more significant. Remote sensing of leaf area index becomes especially useful when we consider the remoteness of, for example, most of the boreal zone and the lack of inventory (or environmental health) data from some regions – remote sensing is the only feasible alternative for these areas. The Fennoscandia region, where the studies in this dissertation are from, represents the most easily accessible area of the whole zone. Satellite images also extend over national borders and interpreting them in some cases can thus provide politically less-biased data on environmental status which is examined through leaf area index or vegetation cover. International efforts in leaf area index estimation are currently made is several networks, for example the VALERI (Validation of Land European Remote Sensing Instruments) (Baret et al. 2005) or in the Land Product Validation subgroup of the Committee on Earth Observation Satellites (Morisette et al. 2005). Leaf area index and other biophysical variables are also needed for terrestrial ecosystem models which integrate remotely sensed data to understand interactions between the biosphere and atmosphere. In this way, it may be possible to obtain a comprehensive view of ecosystem processes at a global level. All these aspects, together with the growing accuracy of the remotely sensed estimates of vegetation growth and status properties provide a strong incentive for continuing to develop remotely sensing techniques. In addition, even though large scale international cooperation and validation activities are already going on, there are still many challenges related to the physical principles of remote sensing to be solved. Nevertheless, the sooner we want information on the state of the biosphere, the sooner we have to begin applying our techniques, even if they are still imperfect and our understanding of the phenomenon is limited.

5. SUMMARY AND CONCLUSIONS

For a considerable time, a widely acknowledged, but poorly explained phenomenon in remote sensing of forests has been the significant difference in the spectral signature of coniferous and broadleaved forests. To give an example, the generally observed lower reflectances of coniferous forests when compared to broadleaved forests has been a puzzling question - why are the reflected spectra of coniferous forests which have the same leaf area and age structure so distinct from similar broadleaved forests? Seeking answers to this question requires physically based understanding of the radiative transfer process in coniferous canopies and identifying the canopy properties responsible for the differences. Several conifer specific properties, for example the highly hierarchic structure of the canopies, have been suggested as possible reasons.

The primary aim of the dissertation was to evaluate the effect of so-far unexplored canopy properties - two aspects of phytoelement grouping - on the radiation reflected from coniferous forest stands.

The first level of phytoelement grouping to be studied, an aspect of macroscale grouping, was crown shape. Results indicated that variation in crown shape leads to considerable differences in the reflectance of coniferous stands: the larger the crown volume, the higher the canopy reflectance at similar leaf area index and canopy closure. A comparison of stands revealed that in denser stands (with a higher canopy closure) single scattering from tree crowns was responsible for the reflectance difference between the different crown shapes, whereas in stands with a smaller canopy closure the single scattering from ground dominated the stand reflectance. A general conclusion is that appropriate parameterization of crown shape in future applications in optical remote sensing of coniferous stands may be essential. To support the choice and application of crown shape, an empirically based simple geometric model, belonging to the family of Lamé curves, was derived for Scots pine crowns. Relatively accurate estimates of the crown maximum radius and its height, parameters needed for application of the model, were obtained using breast height diameter and tree height. The shape coefficient, however, was not clearly related to stand variables and thus hinders the application of the shape model as such.

Next, the effect of a second aspect of phytoelement grouping, the grouping of needles into shoots, on coniferous stand reflectance was evaluated. For this purpose, a new semi-physical forest reflectance model, PARAS, was developed. It is a simple parameterization model for taking into account the effect of within-shoot scattering on coniferous canopy reflectance. The model uses a relationship between photon recollision probability and leaf area index for simulating forest reflectance. The recollision probability is a measurable, wavelength independent variable which is defined as the probability with which a photon scattered in the canopy interacts with a phytoelement again. The results demonstrated for the first time and quantitatively that a major improvement in simulating coniferous canopy reflectance in near-infrared (NIR) is achieved by simply accounting for the within-shoot scattering. In other words, the low NIR reflectances observed in coniferous areas are mainly due to within-shoot scattering.

To support the modeling work, the spectral and directional reflectance properties of typical boreal forest understory species were measured. Relatively large differences between species were found: wax-leaved shrubs (e.g. lingonberry and blueberry) proved to be strong forward scatterers, whereas lichen and soft-leaved dwarf shrubs (e.g. heather) were strong backscatterers. In addition, crown and canopy transmittances were measured to provide support for understanding the role of understory vegetation on stand reflectance.

The second aim of the dissertation was to test the use of two types of retrieval methods, those utilizing satellite images and stand properties in the technique (as in various physically based forest reflectance models) and those using only satellite images, for a currently widely interesting vegetation biophysical variable, the leaf area index.

The results indicated that whether using a forest reflectance model or a spectral vegetation index, a NIR and a MIR band from the satellite image should be included in the retrieval method and the currently widely used NDVI should not be applied in coniferous regions. Possible sources of error which were identified in the inversion of the physically based forest reflectance model and which should be further evaluated in future work were the incorrect parameterization of the understory vegetation and canopy cover, and the missing of a within-shoot scattering correction in the model. A common conclusion made from the results of the inversion studies and from the development of the PARAS model (in the first part of the dissertation) supports integrating a shoot scattering phase function into physically based models that are applied in coniferous dominated areas. At a more general level, the choice of the leaf area index retrieval method itself should be made on the data available. If only an image is available and there is, for example, no predefined, reliable look-up table to run a physically based model through, spectral vegetation indices are a feasible choice.

REFERENCES

Asner, G. 1998. Biophysical and biochemical sources of variability in canopy reflectance. Remote Sensing of Environment 64: 234-253.

Atzberger, C. 2004. Object-based retrieval of biophysical canopy variables using artificial neural nets and radiative transfer models. Remote Sensing of Environment 93: 53-67.

Baret, F., Clevers, J. & Steven, M. 1995. The robustness of canopy gap fraction estimates from red and near-infrared reflectances: a comparison of approaches. Remote Sensing of Environment 54: 141-151.

-, Guyot, G., Begue, A., Maurel, P. & Podaire, A. 1988. Complementarity of middle infrared with visible and near-infrared reflectance for monitoring wheat canopies. Remote Sensing of Environment 26: 213-225.

-, Vanderbilt, V., Steven, M. & Jacquemoud, S. 1994. Use of spectral analogy to evaluate canopy reflectance sensitivity to leaf optical properties. Remote Sensing of Environment 48: 253 – 260.

-, Weiss, M., Allard, D., Garrigue, S., Leroy, M., Jeanjean, H., Fernandes, R., Myneni, R., Privette, J., Morisette, J., Bohbot, H., Bosseno, R., Dedieu, G., Di Bella, C., Duchemin, B., Espana, M., Gond, V., Fa Gu, X., Guyon, D., Lelong, C., Maisongrande, P., Mougin, E., Nilson, T., Veroustraete, F., & Vintilla, R. 2005. VALERI: a network of sites and a methodology for the validation of medium spatial resolution land satellite products. Remote Sensing of Environment, accepted.

Bonan, G. 1995. Land-atmosphere interactions for climate system models: coupling biophysical, biogeochemical, and ecosystem dynamical processes. Remote Sensing of Environment 51: 57-73.

Brown, L., Chen, J., Leblanc, S. & Cihlar, J. 2000. A shortwave infrared modification to the simple ratio for LAI retrieval in boreal forests: an image and model analysis. Remote Sensing of Environment 71: 16-25.

Böttcher, H. 2003. Remote sensing of understorey leaf area index (LAI): A case study of an Estonian forest landscape using SPOT-4 satellite data and a forest reflectance model. Master of Science thesis, Georg-August-Universität Göttingen, Institut für Bioklimatologie.

Campbell, G. 1981. Fundamentals of radiation and temperature relations. In: Lange, O., Nobel, P., Osmond, C. & Ziegler, H. (Eds): Physiological Plant Ecology I. Responses to the physical environment. Encyclopedia of Plant Physiology, 12A. p. 11-40.

Cannell, M. 1989. Physiological basis of wood production: a review. Scandinavian Journal of Forest Research 4: 459-490.

Cescatti, A. 1997a. Modelling the radiative transfer in discontinuous canopies of asymmetric crowns. I. Model structure and algorithms. Ecological Modelling 101: 263-274.

-, 1997b. Modelling the radiative transfer in discontinuous canopies of asymmetric crowns. II. Model testing and application in a Norway spruce stand. Ecological Modelling 101: 275-284.

Chandrasekhar, S. 1950. Radiative transfer. Oxford University Press, London, UK. 393 p.

Chen, J. 1996. Optically based methods for measuring seasonal variation of leaf area index in boreal conifer stands. Agricultural and Forest Meteorology 2-4: 135-163.

- & Black, T. 1992. Defining leaf area index for non-flat leaves. Plant, Cell and Environment 15: 421-429.

- & Cihlar, J. 1996. Retrieving leaf area index of boreal conifer forests using Landsat TM images. Remote Sensing of Environment 55: 153-162.

- & Leblanc, S. 1997. A four-scale birectional reflectance model based on canopy architecture. IEEE Transactions on Geoscience and Remote Sensing 35: 1316-1337.

-, Leblanc, S.G., Miller, J.R., Freemantle, J., Loechel, S.E., Walthall, C.L., Innanen, K.A. & White, H.P. 1999. Compact airborne spectrographic imager (CASI) used for mapping biophysical parameters of boreal forests. Journal of Geophysical Research 104(D22): 27 945-27 958.

-, Pavlic, G., Brown, L, Cihlar, J., Leblanc, S.G., White, H.P., Hall, R.J., Peddle, D.R., King, D.J., Trofymow, J.A., Swift, E., Van der Sanden, J. & Pellikka, P.K.E. 2002. Derivation and validation of Canada-wide coarse-resolution leaf area index maps using high-resolution satellite imagery and ground measurements. Remote Sensing of Environment 80: 165-184.

-, Rich, P., Gower, S., Norman, J. & Plummer, S. 1997. Leaf area index of boreal forests: Theory, techniques and measurements. Journal of Geophysical measurements 102 D24: 29 429-29 443.

Combal, B., Baret, F., Weiss, M., Trubuil, A., Macé, D., Pragnère, A., Myneni, R., Knyazikhin, Y. & Wang, L. 2002. Retrieval of canopy biophysical variables from bidirectional reflectance using prior information to solve the ill-posed inverse problem. Remote Sensing of Environment 84: 1-15.

Daughtry, C., Biehl, L. & Ranson, K. 1989. A new technique to measure the spectral properties of conifer needles. Remote Sensing of Environment 27: 81-91.

Dawson, T., Curran, P. & Plummer, S. 1998. LIBERTY – modeling the effects of leaf biochemical concentration on reflectance spectra. Remote Sensing of Environment 65: 50-60.

Deblonde, G., Penner, M. & Royer, A. 1994. Measuring leaf area index with the LI-COR LAI-2000 in pine stands. Ecology 75: 1507-1511.

Deschamps, P., Bréon, F., Leroy, M., Podaire, A., Bricaud, J., Buriez, J. & Sèze, G. 1994. The POLDER mission: instrument characteristics and scientific objectives. IEEE Transactions on Geoscience and Remote Sensing 32: 598-615.

Diner, D., Beckert, J., Reilly, T., Bruegge, C., Conel, J., Kahn, R., Martonchik, J., Ackerman, T., Davies, R., Gerstl, S., Gordon, H., Muller, J-P., Myneni, R., Sellers, P., Pinty, B. & Verstraete, M. 1998. Multi-angle imaging spectroradiometer (MISR) instrument description and experiment overview. IEEE Transactions on Geoscience and Remote Sensing 36: 1072-1087.

Eklundh, L. & Harrie, L. 2000. Determination of green phytomass in a northern boreal forest by means of Landsat TM-data and a forest canopy reflectance model. The 28th International Symposium on Remote Sensing of Environment, 27-31 March 2000, Cape Town, South Africa. p. 165-184.

-, Harrie, L. & Kuusk, A. 2001. Investigating relationships between Landsat ETM+ sensor data and leaf area index in a boreal conifer forest. Remote Sensing of Environment 78: 239-251.

-, Hall, K., Eriksson, H., Ardö, J. & Pilesjö, P. 2003. Investigating the use of Landsat thematic mapper data for estimation of forest leaf area index in southern Sweden. Canadian Journal of Remote Sensing 29: 349-362.

Fourty, T., Baret, F., Jacquemoud, S., Schmuck, G. & Verdebout, J. 1996. Leaf optical properties with explicit description of its biochemical composition: Direct and inverse problems. Remote Sensing of Environment 56: 104-117.

Ganapol, B., Johnson, L., Hammer, P., Hlavka, C. & Peterson, D. 1998. LEAFMOD: a new within-leaf radiative transfer model. Remote Sensing of Environment 63: 182-193.

Gemmell, F. 1999. Estimating conifer forest cover with thematic mapper data using reflectance model inversion and two spectral indices in a site with variable background conditions. Remote Sensing of Environment 69: 105-121.

- & Varjo, J. 1999. Utility of reflectance model inversion versus two spectral indices for estimating biophysical characteristics in a boreal forest test site. Remote Sensing of Environment 68: 95-111.

-, Varjo, J., Strandström, M. & Kuusk, A. 2002. Comparison of measured boreal forest characteristics with estimates from TM data and lmited ancillary information using reflectance model inversion. Remote Sensing of Environment 81: 365-377.

Gerard, F. & North, P. 1997. Analyzing the effect of structural variaibility and canopy gaps on forest BRDF using a geometric-optical model. Remote Sensing of Environment 62: 46-62.

Goel, N. 1989. Inversion of canopy reflectance models for estimation of biophysical parameters from reflectance data. In Asrar, G. (Ed.): Theory and applications of optical remote sensing. John Wiley & Sons, Inc. New York, USA. p. 205-251.

Govaerts, Y. & Verstraete, M. 1998. Raytran: A Monte Carlo ray-tracing model to compute light scattering in three-dimensional heterogeneous media. IEEE Transactions on Geosciences and Remote Sensing 36: 493-505.

Gower, S. & Norman, J. 1991. Rapid estimation of leaf area index in conifer and broadleaved plantations. Ecology 72: 1896-1900.

Horler, D. & Barber, J. 1981. Principles of remote sensing of plants. In: Plants and the Daylight Spectrum. Proceedings of the First International Symposium of the British Photobiology Society, Leicester, 5 – 8 January 1981, UK. Ed: Smith, H. Academic Press, London.

Horn, H. 1971. The adaptive geometry of trees. Monographs in population biology, 3. Princeton University Press, Princeton, New Jersey, USA.144 p.

Huete, A. 1989. Soil influences in remotely sensed vegetation-canopy spectra. In Asrar, G. (Ed.). Theory and applications of optical remote sensing. John & Wiley Sons, Inc. p. 107-141.

Häme, T. 1991. Spectral interpretation of changes in forest using satellite scanner images. Acta Forestalia Fennica 222: 1 – 111.

Häme, T., Salli, A., Andersson, K & Lohi, A. 1997. A new methodology for the estimation of biomass of conifer-dominated boreal forest using NOAA AVHRR data. International Journal of Remote Sensing 18: 3211-3243.

Jacquemoud, S. & Baret, F. 1990. PROSPECT: a model of leaf optical properties spectra. Remote Sensing of Environment 34: 75-91.

-, Baret, F., Andrieu, B., Danson, M. & Jaggard, K. 1995a. Extraction of vegetation biophysical parameters by inversion of the PROSPECT+SAIL models on sugar beet canopy canopy reflectance data. Application to TM and AVIRIS sensors. Remote Sensing of Environment 52: 163-172.

-, Verdebout, J., Schmuck, G., Andreoli, G. & Hosgood, B. 1995b. Investigation of leaf biochemistry by statistics. Remote Sensing of Environment 54: 180-188.

Jakubauskas, M.E. & Price, K.P. 1997. Empirical relationships between structural and spectral factors of Yellowstone lodgepole pine forests. Photogrammetric Engineering & Remote Sensing 63:1375-1381.

Jennings, S., Brown, N. & Sheil, D. 1999. Assessing forest canopies and understorey illumination: canopy closure, canopy cover and other measures. Forestry 72: 59-73.

Jonckheere, I., Fleck, S., Nackaerts, K., Muys, B., Coppin, P., Weiss, M. & Baret, F. 2004. Review of methods for in situ leaf area index determination. Part 1. Theories, sensors and hemispherical photography. Agricultural and Forest Meterology 121: 19-35.

Jordan, C. 1969. Derivation of leaf-area index from quality of light on the forest floor. Ecology 50: 663-666.

Jupp, D. and Strahler, A. 1991. A hot spot model for leaf canopies. Remote Sensing of Enviroment 38: 193-210.

Kaasalainen, S. & Rautiainen, M. 2005. Hotspot reflectance signatures of common boreal lichens. Accepted for publication in Journal of Geophysical Research.

Kärkkäinen, L. 2005. Evaluation of performance of tree-level biomass models for forestry modeling and analyses. Finnish Forest Research Institute, Research Paper 940: 1-123.

Kimes, D., Knyazikhin, Y., Privette, J., Abuelgasim, A. & Gao, F. 2000. Inversion methods for physically-based models. Remote Sensing of Environment 18: 381-439.

Knipling, E. 1970. Physical and physiological basis for the reflectance of visible and near-infrared radiation from vegetation. Remote Sensing of Environment 1: 155-159.

Knyazikhin, Y., Kranigk, J., Myneni, R., Panferov, O. & Gravenhorst, G. 1998a. Influence of small-scale structure on radiative transfer and photosynthesis in vegetation cover. Journal of Geophysical Research D103: 6133-6144.

-, Martonchik, J., Myneni, R., Diner, D. & Running, S. 1998b. Synergistic alogorithm for estimating vegetation canopy leaf area index and fraction of absorbed photosynthetically active radiation from MODIS and MISR data. Journal of Geophysical Research D103: 32 257-32 275.

Koop, H. 1989. Forest dynamics- SILVI-STAR: a comprehensive monitoring system. Springer, Berlin, Germany.

Kucharik, C., Norman, J. & Gower, S. 1998. Measurements of branch area and adjusting leaf area index indirect measurements. Agricultural and Forest Meterology 91: 69-88.

Kushida, K., Kim, Y., Tanaka, N. & Fukuda, M. 2004. Remote sensing of net ecosystem productivity based on component spectrum and soil respiration observation in a boreal forest, interior Alaska. Journal of Geophysical Research D109: 6108.

Kuuluvainen, T. & Pukkala, T. 1987. Effect of crown shape and tree distribution pattern on the spatial distribution of shade. Agricultural and Forest Meteorology 40: 215-231.

- & Pukkala, T. 1989. Simulation of within-tree and between-tree shading of direct radiation in a forest canopy: effect of crown shape and sun elevation. Ecological Modelling, 49: 89-100.

Kuusipalo, J. 1985.On the use of tree stand parameters in estimating light conditions below the canopy. Silva Fennica 19: 185-196.

Kuusk, A. 1991a. The Hot-Spot Effect in Plant Canopy Reflectance. Ph.D. Thesis abstract, Tartu University, Estonia. 16 pp.

- 1991b. The hot spot effect in plant canopy reflectance, In Myneni, R. and Ross, J. (Eds.), Photon-Vegetation Interactions. Applications in Optical Remote Sensing and Plant Ecology. p. 139-159.

- 2001. A two-layer canopy reflectance model. Journal of Quantitative Spectroscopy and Radiative Transfer 71: 1-9.

- Lang, M. & Nilson, T. 2004. Simulation of the reflectance of ground vegetation in sub-boreal forests. Agricultural and Forest Meteorology 126: 33-46.

- & Nilson, T. 2000. A directional multispectral forest reflectance model. Remote Sensing of Environment 72: 244-252.

- & Nilson, T. 2001. Testing directional properties of a forest reflectance model. Journal of Geophysical Research D11: 12 011-12 021.

-, Nilson, T. & Paas, M. 2002. Angular distribution of radiation beneath forest canopies using a CCD-radiometer. Agricultural and Forest Meteorology 110: 259-273.

Lacaze, R. & Roujean, J-L. 2001. G-function and Hot SpoT (GHOST) reflectance model: Application to multi-scale airborne POLDER measurements. Remote Sensing of Environment 76: 67-80.

Lang, A. 1991. Application of some of Caucy's theorems to estimation of surface areas of leaves, needles and branches of plants and light transmittance. Agricultural and Forest Meterology 55: 191-212.

Lang, M., Kuusk, A., Nilson, T., Lükk, T. Pehk, M. & Alm. G. 2002. [Internet site]. Reflectance spectra of ground vegetation in sub-boreal forests. Available from: http://www.aai.ee/bgf/ger2600/. [Cited May 8, 2002].

Law, B. & Waring, R. 1994. Remote sensing of leaf area index and radiation intercepted by understory vegetation. Ecological Applications 4: 272-279.

Leblanc, S., Bicheron, P., Chen, J., Leroy, M. & Cihlar, J. 1999. Investigation of directional reflectance in boreal forests with an improved four-scale model and airborne POLDER data. IEEE Transactions on Geoscience and Remote Sensing 37: 1396-1414.

Leith, H. & Whittaker, R. 1975. Primary productivity of the biosphere. Springer-Verlag, New York, USA.

Lewis, P. 1999. Three-dimensional plant modeling for remote sensing simulation studies using the Botanical Plant Modelling System. Agronomie 19: 185-210.

Li, X. & Strahler, A. 1985. Geometric-optical bidirectional reflectance modeling of a conifer forest canopy. IEEE Transactions on Geoscience and Remote Sensing. 24: 906-919.

- & Strahler, A. 1992. Geometric-optical bidirectional reflectance modeling of the discrete crown vegetation canopy. IEEE Transactions on Geoscience and Remote Sensing 30: 276-291.

-, Strahler, A. & Woodcock, C. 1995. A hybrid geometric-optical-radiative transfer approach for modeling albedo and directional reflectance of discontinuous canopies. IEEE Transactions on Geoscience and Remote Sensing 33: 466-480.

Liu, J., Chen, J., Cihlar, J. & Park, W. 1997. A process-based boreal ecosystem productivity simulator using remote sensing inputs. Remote Sensing of Environment 62: 158-175.

Marklund, L. 1988. Biomassafunktioner för tall, gran och björk i Sverige. Report 4 (in Swedish). Department of Forest Survey, Swedish University of Agricultural Sciences, Umeå, Sweden. 73 p.

Martonchik. J., Bruegge, C. & Strahler, A. 2000. A review of reflectance nomenclature used in remote sensing. Remote sensing reviews 19: 9-20.

McDonald, M. 2003. Light and Pigments. In: Photobiology of Higher Plants. John Wiley & Sons, Chichester, West Sussex, UK. p. 1-32.

Middleton, M., Walter-Shea, E., Mesarch, M., Chan, S. & Rusin, R. 1998. Optical Properties of Canopy Elements in Black Spruce, Jack Pine and Aspen Stands in Saskatchewan, Canada. Canadian Journal of Remote Sensing 24: 108-119.

Miller, J., White, H., Chen, J., Peddle, D., McDermid, G., Fournier, R., Sheperd, P., Rubinstein, I., Freemantle, J., Soffer, R., & LeDrew, E. 1997. Seasonal change in understorey reflectance of boreal forests and influence on canopy vegetation indices. Journal of Geophysysical Research 102 (D24): 29 475 - 29 482.

Morisette, J., Privette, J., Baret, F., Myneni, R., Nickeson, J., Garrigues, S., Shabanov, N., Fernandes, R., Leblanc, S., Kalacska, M., Sanchez-Azofeifa, G., Chubey, M., Rivard, B., Stenberg, P., Rautiainen, M., Voipio, P., Manninen, T., Pilant, D., Lewis, T., Iiames, T., Colombo, R., Meroni, M., Busetto, L., Cohen' B., Turner, D., Warner, E. & Petersen, G. 2005. Validation of global moderate resolution LAI Products: a framework proposed within the CEOS Land Product Validation subgroup. Accepted for publication in IEEE Transactions on Geoscience and Remote Sensing.

Muinonen, E. 1995. Metsikön heijastussuhteen ennustaminen geometrisella latvustomallilla. Licenciate of Science thesis (in Finnish), University of Joensuu, Faculty of Forest Sciences.

Myneni, R.B., Asrar, G., & Hall, F.G. 1992. A three dimensional radiative transfer model for optical remote sensing of vegetated surfaces. Remote Sensing of Environment 41: 85-103.

-, Keeling, C., Tucker, C., Asrar, G. & Nemani, R. 1997a. Increased plant growth in the northern high latitutes from 1981 to 1991. Letters to nature, Nature 386.

-, Nemani, R. & Running, S. 1997b. Estimation of global leaf area index and absorbed PAR using radiative transfer models. IEEE Transactions on Geoscience and Remote Sensing 35: 1380-1393.

Nemani, R., Pierce, L., Running, S. & Band, L. 1993. Forest ecosystem process at the watershed scale: sensitivity to remotely-sensed leaf area index estimates. International Journal of Remote Sensing 14:2519-2534.

Niinemets, Ü. & Kull, O. 1995. Effects of light availability and tree size on the architecture of assimilative surface in the canopy of *Picea abies*: variation in needle morphology. Tree Physiology 15: 307-315.

Nilson, T. 1991. Approximate analytical methods for calculating the reflection functions of leaf canopies in remote sensing applications. In Myneni, R. and Ross, J. (Eds.), Photon-Vegetation Interactions. Applications in Optical Remote Sensing and Plant Ecology, Springer-Verlag, Berlin, Germany. p. 161-190.

- 1992. Radiative transfer in nonhomogeneous plant canopies. In Desjardins, R., Gifford, R., Nilson, T. and Greenwood, E. (Eds.), Advances in Bioclimatology. Springer-Verlag, Berlin, Germany. p. 59-88.

- 1999. Inversion of gap frequency data in forest stands. Agricultural and Forest Meteorology 98-99: 437-448.

-, Anniste, J., Lang, M. & Praks, J. 1999. Determination of needle area indices of coniferous forest canopies in the NOPEX region by ground-based optical measurements and satellite images. Agricultural and Forest Meteorology 98-99, 449-462.

- & Kuusk, A. 2002. Simulation of reflectance spectra in boreal coniferous forest. In: J.A. Sobrino (Ed.). Recent Advances in Quantitative Remote Sensing, Proc. 1st

International Symposium, 16-20 September 2002, Torrenta, Valencia, Spain. Publications de la Universitat de València. p. 31-38.

-, Kuusk, A., Lang, M. & Lükk, T. 2003. Forest reflectance models: theoretical aspects and applications. Ambio 33: 534-540.

- & Peterson, U. 1991. A forest canopy reflectance model and a test case. Remote Sensing of Environment 37: 131-142.

- & Peterson, U. 1994. Age dependence of forest reflectance: analysis of main driving factors. Remote Sensing of Environment 48: 319-331.

Norman, J. & Jarvis, P. 1974. Photosynthesis in Sitka spruce (*Picea sitchensis* (Bong.) Carr.). III. Measurements of canopy structure and interception of radiation. Journal of Applied Ecology 11(1): 375-398.

- & Jarvis, P. 1975. Photosynthesis in Sitka spruce (*Picea sitchensis* (Bong.) Carr.). V. Radiation penetration theory and a test case. Journal of Applied Ecology, 12(3): 839-877.

North, P. 1996. Three-dimensional forest light interaction model using a Monte Carlo method. IEEE Transactions on Geosciences and Remote Sensing 34: 946-956.

Oker-Blom, P. & Kellomäki, S. 1982. Theoretical computations on the role of crown shape in the absorption of light by forest trees. Mathematical Biosciences 59: 291-311.

- & Kellomäki, S. 1983. Effect of grouping of foliage on the within-stand and within-crown light regime: comparison of random and grouping canopy models. Agricultural Meteorology 59: 291-311.

-, Kaufman, M. & Ryan, M. 1991. Performance of a canopy light interception model for conifer shoots, trees and stands. Tree Physiology 9: 227-243.

- & Smolander, H. 1988. The ratio of shoot silhouette area to total needle area in Scots pine. Forest Science 34: 894-906.

Olthof, I., King, D. & Lautenschlager, R. 2003. Overstory and understory leaf area index as indicators of forest response to ice storm damage. Ecological Indicators 3: 49-64.

Palmroth, S., Stenberg, P., Smolander, S., Voipio, P. & Smolander, S. 2002. Fertilization has little effect on light-interception efficiency in *Picea abies* shoots. Tree Physiology 22: 1185-1192.

Panferov, O., Knyazikhin, Y., Myneni, R., Szarzynski, J., Engwald, S., Schnitzler, K. & Gravenhorst, G. 2001. The role of canopy structure in the spectral variation of transmission and absorption of solar radiation in vegetation canopies. IEEE Transactions on Geoscience and Remote Sensing 39: 241-253.

Pinty, B., Gobron, N., Widlowski, J.-L., Gerstl, S., Verstraete, M., Antunes, M., Bacour, C., Gascon, F., Gastellu, J.-P. , Goel, N., Jacquemoud, S., North, P., Qin, W. & Thompson, R. 2000 The RAdiation transfer Model Intercomparison (RAMI) Exercise. Journal of Geophysical Research 10: 11 937-11 956.

Rees, W., Tutubalina, O. & Golubeva, E. 2004. Reflectance spectra of subarctic lichens between 400 and 2400 nm. Remote Sensing of Environment 90: 281-292.

Roberts, D., Ustin, S., Ogunjemiyo, S., Greenberg, J., Dobrowski, S., Chen, J. & Hinckley, T. 2004. Spectral and structural measures of northwest forest vegetation at leaf to landscape scales. Ecosystems 7: 545-562.

Ross, J. 1981. The radiation regime and architecture of plant stands. Kluwer Academic Publishers, The Hague, Netherlands. 391 p.

Rouse, J., Haas, R., Schell, J., & Deering, D. 1974. Monitoring vegetation systems in the Great Plains with ERTS. Proceedings of the 3rd Earth Resources Technology Satellite-1 Symposium, 10-14 December 1973, Washington, D.C., USA. NASA SP-351, Scientific and Technical Information Office. p. 309-317.

Running, S. & Coughlan, J.C. 1988. A general model of forest ecosystem processes for regional applications: 1. Hydrologic balance, canopy gas exchange and primary production processes. Ecological Modelling 42: 125-154.

Seed, E. & King, D. 2003. Shadow brightness and shadow fraction relations with effective leaf area index: importance of canopy closure and view angle in mixedwood boreal forest. Canadian Journal of Remote Sensing 29: 324-335.

Sellers, P. 1985. Canopy reflectance, photosynthesis and transpiration. International Journal of Remote Sensing 6: 1335-1372.

Shinozaki, K., Yoda, K., Hozumi, K. & Kira, T. 1964. A quantitative analysis of plant form -the pipe model theory. i. basic analyses. Japanese Journal of Ecology 14: 97-105.

Smith, H. & Morgan, D. 1981. The spectral characteristics of the visible radiation incident upon the surface of the Earth. In: Plants and the Daylight Spectrum. Proceedings of the First International Symposium of the British Photobiology Society, Leicester, 5 – 8 January 1981, UK. Ed: Smith, H. Academic Press, London.

Smith, N., Chen, J. & Black, T. 1993. Effects of clumping on estimates of stand leaf area index using the LI-COR LAI-2000. Canadian Journal of Forest Research 23: 1940-1943.

Smolander, H. & Stenberg, P. 1996. Response of LAI-2000 estimates to changes in plant surface area index in a Scots pine stand. Tree Physiology 16: 345-349.

-, Stenberg, P. & Linder, S. 1994. Dependence of light interception efficiency of Scots pine shoots on structural parameters. Tree Physiology 14: 971-980.

Smolander, S. & Stenberg, P. 2003. A method to account for shoot scale clumping in coniferous canopy reflectance models. Remote Sensing of Environment 88: 363-373.

- & Stenberg, P. 2005. Simple parameterizations for the radiation budget of uniform broadleaved and coniferous canopies. Remote Sensing of Environment 94: 355-363.

Solheim, I., Engelsen, O., Hosgood, B. & Andreoli, G. 2000. Measurement and modeling of the spectral and directional reflection properties of lichen and moss canopies. Remote Sensing of Environment 72: 78-94.

Spanner, M., Pierce, L., Peterson, D. & Running, S. 1990. Remote sensing of temperate coniferous forest leaf area index. The influence of canopy closure, understory vegetation and background reflectance. International Journal of Remote Sensing 11: 95-111.

Stenberg, P. 1996. Correcting LAI-2000 estimates for the clumping of needles in shoots of conifers. Agricultural and Forest Meteorology 79: 1-8.

-, Linder, S., Smolander, H. & Flower-Ellis, J. 1994. Performance of the LAI-200o plant canopy analyzer in estimating leaf area index of Scots pine stands. Tree Physiology 14: 981-995.

-, Nilson, T., Smolander, H. & Voipio, P. 2003. Gap fraction based estimation of LAI in Scots pine stands subjected to experimental removal of branches and stems. Canadian Journal of Remote Sensing 29: 363-370.

Strahler, A. & Jupp, S. 1991. Geometric-optical modeling of forests as remotely-sensed scenes composed of three-dimensional, discrete objects. In Myneni, R. and Ross, J. (Eds.), Photon-Vegetation Interactions. Applications in Optical Remote Sensing and Plant Ecology, Springer-Verlag, Berlin, Germany. p. 415-440.

-, Woodcock, C., Li, X. & Jupp, D. 1984. Discrete-object modeling of remotely sensed scenes. 18th International Symposium on Remote Sensing of Environment, Paris, 1-5 October, France.

Strandström, M. 1999. Landsat TM-kuvalta estimoitavien latvuspeiton ja lehtipinta-alaindeksin käyttökelpoisuus metsän kaukokartoitukseen Keski-Suomessa. Master of Science thesis (in Finnish), University of Helsinki, Department of Forest Resources Management.

Suits, G. 1972. The calculation of the directional reflectance of a vegetative canopy. Remote Sensing of Environment 2: 117-125.

Tucker, C. & Garratt, M. 1977. Leaf optical system modeled as a stochastic process. Applied Optics 16: 635-642.

Turner, D., Cohen, W., Kennedy, R., Fassnacht, K. & Briggs, J. 1999. Relationships between leaf area index and Landsat TM spectral vegetation indices across three temperate zone sites. Remote Sensing of Environment 70: 52-68.

-, Ritts, W., Cohen, W., Gower, S., Zhao, M., Runnig, S., Wofsy, S., Urbanski, S., Dunn, A. & Munger, J. 2003. Scaling gross primary production (GPP) over boreal and deciduous forest landscapes in support of MODIS GPP product validation. Remote Sensing of Environment 88: 256-270.

Verhoef, W. 1984. Light scattering by leaf layers with application to canopy reflectance modeling: the SAIL model. Remote Sensing of Environment 16: 125-141.

Vermote E., Tanre D., Deuze J., Herman M., and Morcrette J.-J. 1997. Second simulation of the satellite signal in the solar spectrum, 6S: An overview. IEEE Transactions on Geoscience and Remote Sensing 35: 675-686.

Verstraete, M. & Pinty, B. 1996. Designing optimal spectral indices for remote sensing purposes. IEEE Transactions on Geoscience and Remote Sensing 34: 1254-1265.

Vogelmann, J. 1990. Comparison between two vegetation indices for measuring different types of forest damage in the northeastern United States. International Journal of Remote Sensing 11: 2281-2297.

Vogelman, S. & Moss, D. 1993. Spectral reflectance measurements in the genus Spaghnum. Remote Sensing of Environment 45: 273-279.

Walter-Shea, E. & Norman, J. 1991. Leaf optical properties. In Myneni, R. and Ross, J. (Eds.), Photon-Vegetation Interactions. Applications in Optical Remote Sensing and Plant Ecology, Springer-Verlag, Berlin, Germany. p. 229 -251.

Walthall, C., Norman, J., Welles, J., Campbell, G. & Blad, B. 1985. Simple equation to approximate the bidirectional reflectance from vegetative canopies and bare soil surfaces. Applied Optics 24(3): 383-387.

Wang, Y., Buermann, W., Stenberg, P., Smolander, H., Häme, T., Tian, Y., Hu, J., Knyazikhin, Y. & Myneni, R. 2004. A new parametrization of canopy spectral response to incident solar radiation: case study with hyperspectral data from pine dominant forest. Remote Sensing of Environment 85: 304-315.

Watson, D. 1947. Comparative physiological studies in the growth of field crops. I. Variation in net assimilation rate and leaf area between species and varieties, and within and between years. Annales Botanicales 11: 41-76.

Weiss, M. & Baret, F. 1999. Evaluation of canopy biophysical variable retrieval performances from the accumulation of large swath satellite data. Remote Sensing of Environment 70: 293-306.

-, Baret, F., Myneni, R., Pragnère, A. & Knyazikhin, Y. 2000. Investigation of a model inversion technique to estimate canopy biophysical variables from spectral and directional reflectance data. Agronomie 20: 3-22.

-, Baret, F., Smith, G., Jonckheere, I. & Coppin, P. 2004. Review of methods for in situ leaf area index (LAI) determination. Part II. Estimation of LAI, errors and sampling. Agricultural and Forest Meteorology 121: 37-53.

White, J.D., Running, S.W., Nemani, R.., Keane, R.E. & Ryan, K.C. 1997. Measurement and remote sensing of LAI in Rocky Mountain montane ecosystems. Canadian Journal of Forest Research 27: 1714-1727.

Williams, D. 1991. A comparison of spectral reflectance properties at the needle, branch, and canopy level for selected conifer species. Remote Sensing of Environment 35: 79-93.

Williams, M., Patterson, P. & Mowrer, T. 2003. Comparison of ground sampling methods for estimating canopy cover. Forest Science 49: 235-246.

Wilson, J. 1960. Inclined point quadrats. New Phytologist 59:1-8.

APPENDIX 1: DESCRIPTION OF THE STUDY SITES.

Empirical data were collected from three test sites (Fig. 1):

The Hirsikangas site in Suonenjoki, central Finland (62^o 38.7 N, 27^o 0.5 E)

- A Scots pine dominated site composed of ~ 400 managed stands on relatively flat land. Typical understory species included *Vaccinium myrtillus* L., *Vaccinium vitis-idaea* L., *Calluna vulgaris* L., lichens (Cladina sp. and Cladonia sp.) and mosses (e.g. *Pleurozium schreberi* (Brid.) Mitt., *Dicranum polysetum* Sw.). Also a 3 x 3 km test site of the VALERI (Validation of Land European Remote Sensing Instruments) network.
- Measurements made at the site and used in this dissertation: Scots pine crown shape, canopy cover, stand inventory, understory BRDF.
- Satellite image: SPOT HRVIR1, August 2003.
- Data used in Studies II, IV, V, VI.

The Saarinen site in Suonenjoki, central Finland (62^o 40.9 N, 27^o 28.7 E)

- A Norway spruce dominated, Scots pine subdominated site composed of ~ 400 plots on relatively flat land. Typical understory species included *Vaccinium myrtillus* L., *Vaccinium vitis-idaea* L, *Maianthemum bifolium* (L.) Schmidt, *Geranium sylvaticum* L.
- Measurements made at the site: stand inventory, leaf area index measurements with the LAI-2000 Plant Canopy Analyzer.
- Satellite image: Landsat 7 ETM, July 2001.
- Data used in Studies III, VIII.

The Puumala site in Puumala, southeastern Finland (61^o 31.6 N, 28^o 42.4 E)

- A Scots pine dominated, Norway spruce subdominated site composed of ~ 400 plots on relatively flat land. Typical understory species included *Vaccinium myrtillus* L., *Vaccinium vitis-idaea* L., *Maianthemum bifolium* (L.) Schmidt, *Geranium sylvaticum* L. Also a MODIS LAI/FPAR product validation site.
- Measurements made at the site: stand inventory, leaf area index measurements with the LAI-2000 Plant Canopy Analyzer.
- Satellite image: Landsat 7 ETM, June 2000.
- Data used in Studies III, VII, VIII.

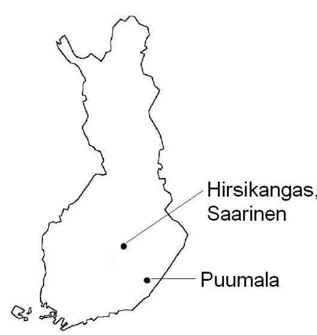

Figure 1. Location of the study sites.