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Indirect estimations and spatial variation in leaf area index of coniferous, deciduous and mixed forest stands in Forsmark and Laxemar

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Abstract

Two sites in Sweden are investigated for a potential deep repository of the nuclear waste, the Laxemar investigation area (57°5’N, 16°7’E) and the Forsmark investigation area (60°4’N, 18°2’E). In the characterisation of these sites, development of site descriptive models is an important part. Leaves are the main surface were an exchange of matter and energy between the atmosphere and the biosphere takes place, and leaf area index (LAI) of the vegetation cover is an important variable correlated to a number of ecophysiological parameters and hereby an important parameter in ecosystem models. In the investigation areas, LAI of boreal and temperate ecosystems were therefore estimated indirectly through optical measurements using the LAI-2000 (LI-COR, Cambridge UK) and TRAC (Tracing Radiation and Architecture of Canopies). On average, measured maximum LAI was 3.40 in Laxemar and 3.43 in Forsmark; minimum LAI was 1.65 in Laxemar and 1.97 in Forsmark. Forest inventory data showed that LAI is positively correlated with basal area, stand height, stand volume and breast height tree diameter. For the coniferous stands, there was also a linearly negative relationship with age. In the Laxemar investigation area, there were no significant relationships for LAI with a satellite derived kNN (kNearest Neighbor) data set with stand height, stand volume and stand age. The kNN data set can therefore not be used to extrapolate measured LAI over the Laxemar investigation area. There were significant relationships between LAI and the normalized difference vegetation index (NDVI) for coniferous, deciduous and mixed forest stands in the Laxemar investigation area. A NDVI image could be used to extrapolate LAI over the entire investigation area. For the Forsmark investigation area, effective LAI for all stands were correlated to NDVI and this relationship could then be used for extrapolation. The effective LAI image was afterwards corrected for average needle to shoot area ratio, woody to total area ratio and element-clumping index for coniferous, deciduous and mixed forest stands. NDVI modelled LAI was used to evaluate the LAI product from Moderate Resolution Imaging Spectroradiometer (MODIS), and the comparison indicated that MODIS LAI was neither correlated to LAI in Laxemar nor in Forsmark. MODIS LAI also was larger than NDVI modelled LAI and it showed large variations at both sites. It is therefore not recommended to use the MODIS LAI product for future LAI estimations in these small investigation areas.

Sammanfattning

Bladyteindex (LAI) har undersökts i boreala och tempererade skogsekosystem i Laxemars undersökningsområde (57°5’N, 16°7’E) i sydöstra Sverige och i Forsmarks undersökningsområde (60°4’N, 18°2’E) i centrala Sverige. Platsbeskrivning av dessa platser genomförs av SKB eftersom de är tilltänkta för ett framtida potentiellt slutförvar av radioaktivt bränsle producerat på kärnkraftverk i Sverige. Det är främst i bladytan som utbyte av material och energi sker och LAI ger härmed en god indikation på ekosystemets produktivitet. I och med denna koppling är LAI en av de viktigaste parametrarna inom ekosytemmodellering och ett viktigt verktyg för SKB i deras platsbeskrivande modeller. LAI är definierat som halva den totala bladytan per enhet markyta.

LAI uppskattades med hjälp av indirekta optiska metoder, dessa uttnyttjar kopplingen mellan lövhalten i träden till strålning som penetrerar trädkronorna. Mätningar genomfördes 11 till 22 april 2005 för att upskatta minimum LAI och 20 till 30 juni 2005 för att uppskatta maximum LAI. Mätningarna genomfördes i bestånd som undersökts av Riksskogstaxeringen och i bestånd som SKB valt ut till att vara representativa för undersökningsområdena. Totalt var det 34 bestånd i Laxemars undersökningsområde och 18 i Forsmarks undersökningsområde. De var av olika karaktär, barrbestånd, lövbestånd och blandat barr- och lövbestånd.

Det mätinstrument som användes var LAI-2000 (LI-COR, Cambridge UK). I den algoritm detta instrument använder för att beräkna LAI har vissa förenklingar gjorts och det som uppskattas är inte det korrekta LAI värdet utan något som kallas för effektivt LAI. Den första förenklingen algoritmen antar är att löven är slumpartat distruberade. Detta är inte korrekt eftersom löven är klumpade på trädkronorna, på trädets grenar och för barrträd är även barren klumpade inom skotten. Klumpningen i trädkronor och på trädgrenar uppskattades med hjälp av mätinstrumentet TRAC (Tracing Radiation and Architecture of Canopies). För klumpning inom skotten krävs dock mätningar på skotten och dessa är komplicerade att genomföra varpå litteraturvärden användes istället. Den andra förenkling i algoritmen är att instrålning inte bara påverkas av löven i trädkronorna utan av hela trädet. Den fraktion av instrålningen som tas upp av icke lövmaterial, dvs trä, måste härmed subtraheras. I lövbestånden uppskattades denna fraktion genom att dela LAI-2000 mätningar från april med LAI-2000 mätningar från juni. För barrträd som är gröna året om är dessa uppskattningar svåra att genomföra och här användes istället litteraturvärden. Korrekta LAI värden beräknades genom korrektion av effektiv LAI för beståndsklumpningen, inomskottsklumpning och genom att subtrahera träts del av effektiv LAI. I genomsnitt var maximum LAI 3,40 i Laxemar och 3,43 i Forsmark, minimum LAI var 1,65 i Laxemar och 1,97 i Forsmark.

I de bestånd som SKB valt ut genomfördes även en skogsinventering, där skogskaraktärerna, trädhöjden, brösthöjdsdiametern, beståndsvolymen och beståndets brösthöjdsålder undersöktes. I genomsnitt fanns det 19,1 m^2 träd ha^{-1} i Laxemar och 20,0 m^2 träd ha^{-1} i Forsmark, brösthöjdsdiametern var 28,0 cm i Laxemar och 27,3 cm i Forsmark, trädhöjden var 17,2 m i Laxemar och 18,9 m i Forsmark, beståndsvolymen var 162 m^3 sk ha^{-1} i Laxemar och 226 m^3 sk ha^{-1} i Forsmark och brösthöjdsåldern var 88 år i Laxemar och 78 år i Forsmark. Av dessa var LAI positivt korrelerade till grundytan, trädhöjden, brösthöjdsdiametern och beståndsvolymen. För barrträden fanns även en negativ korrelation till brösthöjdsåldern.

För att kunna uppskatta LAI på skalor större än ett lokalt bestånd är det nödvändigt att använda sig av fjärranalysmodeller. I dessa kopplas information från fältundersökningar till satellitbaserad information för att extrapolera ut fältundersökningarna spatialt. Över Laxemars undersökningsområde fanns ett kNN-dataset med information om trädhöjd, beståndsvolym och beståndets ålder. Men även om LAI var kopplat till dessa parametrar när de mätts i skogsinventeringen var de ej kopplade till samma information i kNN datasetet. kNN datasetet kunde därför inte användas till att extrapolera ut LAI. Satelliter mäter strålning i olika våglängdsband som

reflekteras från marken. Löv är fotosyntiserande och absorberar strålning i vissa band medan de reflekterar strålning i andra. I det s.k. normalized difference vegetation index (NDVI) använder man sig av detta och kombinerar information om strålning i det röda och nära infraröda för att forma ett index. Korrelationen mellan LAI och NDVI undersöktes och signifikanta samband fanns mellan LAI och NDVI för barr, löv och blandbestånd i Laxemars undersökningsområde. En NDVI karta kunde härmed användas till att extrapolera ut maximum LAI över Laxemars undersökningsområde. I Forsmark fanns ingen korrelation mellan LAI och NDVI, däremot fanns en korrelation mellan effektiv LAI och NDVI när alla bestånd användes. Denna korrelation användes till att extrapolera effektiv LAI över undersökningsområdet. Denna effektiva LAI karta korrigerades i efterhand med medelvärden av beståndsklumpning, inomskottsklumpning och fraktionen trä för barrskog, lövskog och blandskog.

MODIS (Moderate Resolution Imaging Spectroradiometer) är en ny sensor på satteliterna Terra (EOS AM) och Aqua (EOS PM). Denna sensor ger en uppskattning av LAI med en pixelstorlek på en kilometer. NDVI modellerade LAI värden användes till att utvärdera dessa MODIS uppskattade LAI värden. Varken i Laxemar eller i Forsmark hittades någon korrelation till MODIS uppskattningen av LAI. På båda platserna var dessutom MODIS LAI högre och hade mycket större variation än vad NDVI modelerade LAI hade. MODIS LAI bör därmed inte användas till att uppskatta LAI i dessa regionala undersökningsområden i framtiden.

Contents

1 Introduction

The Swedish Nuclear and Fuel Waste Management Co. (SKB) has the responsibility to investigate and present detailed proposals of how the spent nuclear fuel in Sweden should be taken care of. Two sites in Sweden are investigated for a potentially deep repository of the nuclear waste, the Laxemar and the Forsmark investigation areas. In the work of siting a deep repository, extensive site investigations will precede the coming proposal. An important part of the site characterisation is the development of site descriptive models that gives an integrated description of the current state of the regions and the processes that might affect this state in the future /Lindborg 2005/. Important processes in these site descriptive models are the hydrological processes as well as the carbon, nitrogen and phosphorous cycling. In this context a description of the spatial distribution of LAI may serve as an additional tool for describing element cycling.

The work of siting a deep repository also includes a safety assessment, where different types of scenarios are analysed. If a future leakage occurs, the radioactive isotopes could then end up in the ecosystems above the repository. The fate of the radionuclides and their possible radiological impacts are then highly determined by ecosystem element cycling since radioactive isotopes often follow the same pathway as stable elements vital for the vegetation /Greger 2004/. It could also be that the ecosystems are affected by the handling of the waste and the activity around the repository. To notice this possible change, it is of main importance to have knowledge about the ecosystem functions beforehand, both for the understanding of an unaffected ecosystem and to have something to compare the damaged ecosystem with.

Leaves are the main surface were an exchange of matter and energy between the atmosphere and the biosphere takes place, and leaf area index (LAI) of the vegetation cover is an important variable correlated to a number of ecophysiological parameters, e.g. photosynthesis, autotrophic respiration, net primary production and transpiration and other ecosystem processes such as litter fall, root production, nutrient availability and soil respiration /Bonan 1993, Chen and Cihlar 1995, Coble et al. 2001, Fassnacht and Gower 1997, Jose and Gillespie 1997, Sakai and Akiyama 2005/. It has therefore been highlighted as an important variable both in regard to the study of global carbon budgets for quantifying and scaling up these ecophysiological processes /Chen et al. 1997/ as well as in describing them on smaller scales. LAI, defined as half the total leaf area per unit surface area /Chen and Black 1992/, is due to these features an important parameter in ecosystem models /Chen and Cihlar 1995/. Furthermore, LAI responds fast to stress factors and may serve as an indicator of changes in the ecosystem /Myneni et al. 1997a/.

On a local stand scale there are different ways to estimate LAI and they can be separated into direct methods (destructive sampling or litterfall collection) and indirect methods (optical measurements) /Chen et al. 1997/. Direct methods are more costly, time consuming and destructive for the ecosystems, but have often been used to validate the results from the indirect methods /Chen et al. 1997, Gower et al. 1999, Law et al. 2001, Eriksson et al. 2005/. The indirect methods, (the optical measurements) use the incident radiation transmitted through the canopy to estimate LAI. These measurements are straightforward and they give results quickly, cheaply and large areas can be covered. The method is called the gap fraction method as it is based on the fraction of the sky that can be seen from beneath the canopy, i.e. the gaps in the canopy. The gap fractions saturate at high LAI and this method can only be used up to a LAI of six /Leblanc and Chen 2001/. The method is used by several of the commercially available instruments; among them the LAI-2000 plant canopy analyzer (PCA). A limitation with the method is that the algorithm used is simplified and measurements done in complex natural canopies need corrections.

The first simplification is that the algorithm requires random foliage distribution. The foliage distribution can be separated into two parts, foliage angular distribution and foliage spatial distribution. The foliage angular distribution describes the angles of the leaves and needles in relation to the incoming solar radiation and this part is random in many natural canopies. The problem is the second part, the foliage spatial distribution, which describes where in space the foliage is distributed. Foliage is not randomly distributed in space since needles and leaves grow clumped in tree crowns, on branches and at the shoots. The LAI-2000 instrument therefore underestimates LAI in natural clumped canopies /Chen and Cihlar 1995/. TRAC (Tracing Radiation and Architecture of Canopies) is an instrument that was developed to handle this problem (Introduced by /Chen and Cihlar 1995/). In addition to the gap fraction, TRAC measures the sizes of the gaps in the canopy and this gives an indication of the large scale clumping of a canopy /Chen and Cihlar 1995/. Sizes of the gaps are only affected by clumping on scales larger than the shoots and for corrections of the within shoot clumping, shoot measurements has to be done.

The second drawback with the optical measurements is that incoming solar radiation is affected by the whole plant and not only by the leafy material in the canopies. The LAI-2000 therefore estimates more of a plant area index (also called effective LAI) than LAI. To receive LAI, the fraction of woody area has to be subtracted from effective LAI /Gower et al. 1999/.

To estimate LAI on larger scales than the local stands, remote sensing can be used. Satellites measure radiation at different spectral ranges reflected from the surface and the remotely sensed images have large spatial and temporal coverage /Boresjö Bronge 2004/. Leaves are photosynthetically active material and they absorb solar radiation in specific spectral bands, while they reflect radiation in other bands of the solar spectrum /Campbell 2002/. Vegetation indexes, such as the normalized difference vegetation index (NDVI) and the simple ratio index (SR), combine information from the red and the near infrared bands to form ratios. In previous studies, site-specific statistical relationships have been found between these indexes and LAI for different vegetation types /Turner et al. 1999, Eklundh et al. 2003, Boresjö Bronge 2004, Stenberg et al. 2004/.

This study investigates LAI of boreal and temperate ecosystems in the Laxemar investigation area in Southeastern Sweden and in the Forsmark investigation area in central Sweden. There are three general aims. Firstly, I will indirectly estimate minimum and maximum LAI of coniferous, deciduous and mixed forest stands of the investigation areas and the relationship between LAI and stand characteristics will be analyzed to explain the spatial variation in LAI. Secondly, I will investigate the relationship between LAI and satellite derived information and this relationship will be used to extrapolate LAI spatially over the investigation areas. Thirdly, I will compare the spatially extrapolated LAI with LAI estimated by MODIS (Moderate Resolution Imaging Spectroradiometer).

2 Theory

2.1 The gap fraction method

The penetration of direct solar beam radiation through a forest canopy is influenced by the position and angles of the elements of the canopy, i.e. the leaves, needles, branches and stems /Kucharik et al. 1998/. The probability ($P(\theta)$) for a direct beam to penetrate through a plant canopy at some angle (θ) can be described by Millers theorem /Stenberg et al. 1994, Chen et al. 1997, Eriksson et al. 2005/:

$$P(\theta) = \exp[-G(\theta)L_e(\theta)(\cos(\theta))^{-1}] \qquad \text{(Equation 1)}$$

where $P(\theta)$ is the gap fraction measured by the LAI-2000 instrument, $G(\theta)$ is the canopy extinction coefficient and L_e is effective LAI for the angle (θ). The canopy extinction coefficient is an estimate of the fraction of the foliage projected onto a plane perpendicular to direction of the beam (θ) and it describes the angular distribution of the foliage. The gap fractions saturate at high LAI and this method can only be used up to a LAI of about 6 /Leblanc and Chen 2001/.

Effective LAI is calculated through an assumption of random angular distribution and an integration of (Equation 1):

$$L_e = 2_o\int^{\pi/2} \ln[1/P(\theta)]\cos(\theta)\sin(\theta)d(\theta) \qquad \text{(Equation 2)}$$

Effective LAI is not equal to the true LAI value because, firstly, all elements in the canopy contribute to stop the beam radiation and some of these elements are woody material, secondly, this equation assumes a random spatial distribution of the foliage, but natural canopies are clumped, and leaves and needles are grouped in shoots, branches and tree crowns /Chen and Cihlar 1995/. LAI can therefore be described by /Chen 1996/:

$$L = (1-\alpha)L_e\gamma_E(\Omega_E)^{-1} \qquad \text{(Equation 3)}$$

Where L is LAI, α woody to total area ratio, L_e effective LAI, γ_E needle to shoot area ratio and Ω_E is the element-clumping index describing the effect of clumping on a scale larger than the shoots.

The woody to total area ratio (α) describes the fraction woody area in the canopy. In deciduous stands, that looses their leaves in winter, the woody to total area ratio can be estimated by dividing LAI-2000 measurements done in the stand when leaves are absent with measurements done when leaves are present /Eriksson et al. 2005/. For coniferous stands, that are evergreen, woody to total area ratio is more difficult. In destructive methods needle and branch area can be decreased gradually through removal of branches while LAI-2000 measurements are done /Smolander and Stenberg 1996/.

In optical measurements, the smallest unit considered is leaves in deciduous stands and shoots in coniferous stands. In deciduous ecosystems, there is no clumping within a leaf whereby it is not necessary with a correction on this scale /Eriksson et al. 2005/. In coniferous stands, needles are clumped within the shoots and to estimate LAI a correction for the overlap of the needles is therefore needed. In coniferous stands, LAI-2000 measurements rather estimate the shoot silhouette area index than the needle area index /Stenberg 1996a/. The ratio of the shoot silhouette area to total needle area (STAR) can be estimated through measurements of shoots and photographs of their silhouette. The correction factor, or the needle to shoot area ratio (γ_E), can then be estimated through:

$$\gamma_E = (4\mathrm{STAR})^{-1} \qquad \text{(Equation 4)}$$

where the factor 4 is necessary since LAI is defined as half the total leaf area and since needles are convex /Stenberg 1996a/.

The element-clumping index (Ω_E) corrects effective LAI for clumping on scales larger than the shoots and it can be estimated with TRAC /Chen and Cihlar 1995/. TRAC measures incoming solar radiation at a frequency of 32 Hz. The operator walks with the instrument at a slow steady pace and both sizes and fractions of the canopy gaps are thus measured, i.e. the canopy gap size distribution. To estimate how clumped the canopy is, measured canopy gap size distribution is compared with a theoretical gap size distribution, where the gaps are randomly distributed /Chen and Cihlar 1995/:

$$\Omega_E = [1+(F_m-F_{mr})]\ln[F_m](\ln[F_{mr}])^{-1} \qquad \text{(Equation 5)}$$

where F_m is the measured total canopy gap fraction and F_{mr} the gap fraction in random distributed foliage. TRAC measurements are done in bright solar conditions. The gap fraction of a canopy varies with solar angle, and to receive a correct element-clumping index, measurements should be recorded at different angles throughout the day. /Leblanc and Chen 2001/ have shown that measurements recorded within zenith angles of 35°–60° give estimates that are reasonably close to the mean clumping index of all angles.

2.2 Remote sensing

LAI is related to reflected radiance and this is applied in remote sensing /Campbell 2002/. A large portion of the red part of the spectra is taken up by chlorophyll during photosynthesis while radiation in the near infrared part of the spectra is highly transmitted due to structures within the leaves /Campbell 2002/. Ratios (vegetation indexes) between these two wavelength bands are used in remote sensing for estimating for example LAI. An optimal vegetation index is sensitive to LAI while it is insensitive to perturbation factors /Verstraete and Pinty 1996/ such as reflectance from the atmosphere, stand characteristics, topography, foliage distribution, geometry of the sun and the sensor, soil properties, reflectance from woody material, background reflectance and ground vegetation /Ardö 1998/. One index that is commonly used in LAI investigations is the normalised difference vegetation index (NDVI) defined as the difference between the red and the near infrared bands divided by the sum of the same bands.

A kNN (k Nearest Neighbour)-dataset with stand volume, stand height and stand age that covers the complete forest area of Sweden has been developed /Reese et al. 2003/. The method used is the k Nearest Neighbour (kNN) method, where a couple of reference stands with known mean values are used to derive data for the other pixels. The stands are weighted differently depending on their distance to the pixel to be calculated /Reese et al. 2003/. The mean stand characteristic values are taken from forest inventories done by the Swedish NFI (National Forest Inventory) and the satellite data used are the bands 3, 4, 5 and 7 from Landsat 7. This dataset could be a strong tool in investigations and management of the Swedish forests.

MODIS (Moderate Resolution Imaging Spectroradiometer) is a new sensor on the Terra (EOS AM) satellite, launched in 1999 and the Aqua (EOS PM) satellite launched in 2002. For the MODIS sensor a number of standard products for the terrestrial surface are available and one of them is LAI coverage, given a value between 0 and 10. The main advantage with the MODIS data is that it has a high temporal resolution; MODIS cover the entire earth every 1 to 2 days and the LAI product is based on 8 days composites. A drawback, though, is the spatial resolution, where the LAI product has a spatial resolution of 100 ha. The launching of the TERRA satellite with the MODIS sensor started a new era in remote sensing /Myneni et al. 2002/, and as its products began to be available on the Earth Observing System data gateway, the products has been widely used in all kinds of applications.

3 Material and method

3.1 Site description

The investigations took place at the Laxemar investigation area, situated 25 km north of Oskarshamn in southern Sweden (57°5’N, 16°7’E), and at the Forsmark investigation area situated 70 km north-northeast of Uppsala in the center of Sweden (60°4’N, 18°2’E). Climate is temperate at both sites. In Laxemar, mean annual temperature in 2005 was 7.3°C with the warmest average monthly temperature of 18.6°C in July and the coldest average monthly temperature of –1.4°C in March. In Forsmark, mean annual temperature 2005 was 6.9°C with the warmest average monthly temperature of 17.7°C in July and the coldest average monthly temperature of –3.2°C in March. Annual precipitation for the same period was 435 mm for Laxemar and 437 mm for Forsmark. The growing season 2005 started the 3rd of April and ended the 14th of November in Laxemar and in Forsmark it started the 3rd of April and ended the 13th of November (threshold 5°C). Dry Scots pine (*Pinus sylvestris*) forests dominate the Laxemar investigation area, but in the areas with deeper soil layers Norway spruce (*Picea abies*) forests are also common. The deciduous forests, mainly Pedunculate oak (*Quercus robur)*, are important constituents along the coast, and this makes the mixed forests the second most abundant forest type. In the Forsmark investigation area, the dominant forests are Scots pine and Norway spruce. Birch (*Betula pendula*), alder (*Alnus glutinosa*) and rowan (*Sorbus acuparia*) dominate the deciduous forests in Forsmark /Lindborg 2005, 2006/.

3.2 The forest stands

The National forest inventory has made inventories of the Swedish forests since 1924 and some of their inventories have been done in stands situated in the region of these investigation areas. Sites, where inventories were made after 1990 were chosen. At some sites, inventories were made twice and in these cases the latest inventory were used. SKB has also chosen 12 representative forest stands for the Laxemar investigation area and 4 for the Forsmark investigation area to be used for intensive studies. In all, 34 stands in Laxemar and 18 stands in Forsmark were selected for this study (Table 4-2 and 4-3). They were of different character; it was coniferous, deciduous and mixed deciduous and coniferous forest stands. The stands were classified as being homogenous or mixed depending on if the fraction of one single group (Scots pine, Norway spruce, birch and other deciduous tree species) exceeds 0.7 /Praktisk Skogshandbok 1994/. The size of the stands varies between 400 m^2 and 1,250 m^2.

3.3 Forest stand Inventories

At the representative stands chosen by SKB, two measurements of basal area were made with a relascope. Stem density was measured by counting all trees with a height above 1.80 m within a circle with a radius of 5.65 m. In the Forsmark investigation area, 5 circles per ecosystems were counted and in the Laxemar investigation area one circle per ecosystem was counted. Ten trees that well represented the species and size distributions of the stands were chosen, height was measured with a Vertex III together with a T3 transponder (Haglöf Sweden AB, Långsele) and circumference was measured at breast height (1.3 m). To estimate the stand breast height age, the breast height age of the two trees with largest diameter in a circular area with the radius of ten meters were estimated by drilling a tree core at breast height into the center of each tree and then counting the tree rings.

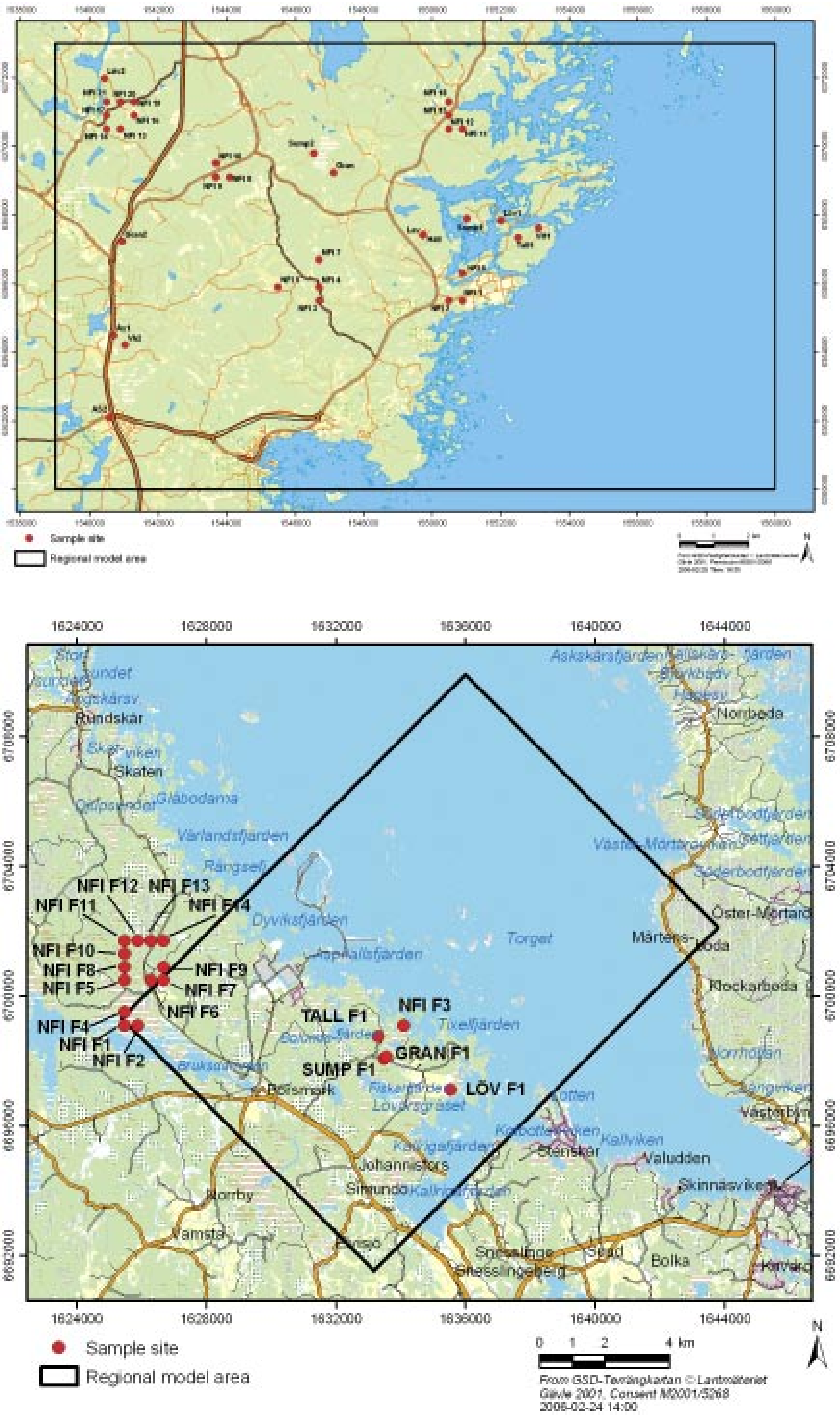

Figure 3-1. Map over (a) the Laxemar investigation area and (b) the Forsmark investigation area. The dark line marks the borders of the investigation areas and the red dots marks the stands investigated.

The stem volumes of the individual trees measured in the stands were approximated to an estimate of the tree volume of the total stands. For this, Brandels volume functions for individual trees were used for Scots pine, Norway spruce and birch /Brandel 1990/. In the base function of Brandel, height and breast height diameter of the tree is needed and the functions used were 2111-190-01 for pine, 2121-190-01 for spruce and 2131-190-01 for birch. For alder, volume function number 14 from /Eriksson 1973/ was used and for oak, a volume table by /Hagberg and Matérn 1975/ was used. In each stand, the average volume of the individual trees was calculated. For the mixed stand, i.e. sump F1 (Table 4-1), the average volume of all species was calculated and the fractions of the different species were then used to estimate a stand average. Then, the average cross section area of the trees was calculated with the breast height diameter. The estimated average volume was then divided with this cross-section area to get tree volume m^{-2}. Basal area is $m^2\ ha^{-1}$ and by multiplying the tree volume m^{-2} with the basal area, the average tree volume ha^{-1} was received. For some deciduous ecosystems, there were problems with the equations. For sump 2, equations from Brandel could not be used since it is a swampy ecosystem. For Löv F1 and Löv 2, no equations could be found for maple (*Acer platanoides)* and lime (*Tilia cordata*) and the volume of these ecosystem could not be calculated either.

3.4 The LAI optical measurements

To estimate LAI, the parameters of effective LAI (L_e), woody to total area ratio (α), needle to shoot area ratio (γ_E) and the element-clumping index (Ω_E) are needed, (Equation 3). Firstly, L_e values were optically measured with a LAI-2000 PCA (Plant Canopy Analyzer) (LI-COR, Cambridge UK). Measurements were made between the 11th and 22nd of April to retrieve minimum LAI and between the 20th and 30th of June to get maximum LAI. Measurements were made either at dusk, dawn or under cloudy sky conditions to get diffuse radiation from all directions of the atmosphere. In Laxemar two measurements in April were taken away since they were made too late in the evening. For the above canopy readings, one sensor were placed in either a tower rising above the canopy or in a large open field. In the open field, the sensor was placed with a distance to the closest trees of at least 3.5 times the height of the trees. The within stand measurements were made by walking 3 transects through the stands, evenly distributed along these; transmitted radiance were measured about every 1.5 meter. The number of measurements was between 45 and 60, depending on the size of the stand. The field of view of the sensor within the stand had the same compass azimuth angle, as the sensor out in the field. View restrictors of 270° were used to restrict the incoming radiation and to prevent the influence of the operator. A software program, C2000, coming with the instrument, coordinated the above and below canopy readings in time with no larger time difference than 7.5 seconds. Effective LAI was then calculated, using an approximation to (Equation 2), by the C2000 software.

For homogenous deciduous stands, woody to total area ratio (α) were estimated with LAI-2000 measurements done in April, when leaves are absent, by dividing it with the LAI-2000 measurement made in June. Coniferous forests are evergreen in these areas and the woody to total area ratio cannot be easily estimated. Literature values were used, where the pine value was taken from /Smolander and Stenberg 1996/ and the spruce value from /Gower et al. 1999/. For spruce, no value was found for *Picea abies* and an average of values for *Picea mariana* and *Picea sitchensis* was used instead. One average woody to total area ratio was calculated for birch and one for the rest of the deciduous trees (Table 3-1). In these calculations, values from both Forsmark and Oskarshamn were used, since there were too few deciduous stands in Forsmark. Average woody to total area ratio for pine, spruce, birch and the rest of the deciduous trees were then calculated. To get the woody to total area ratio for the mixed and coniferous stands, fractions of their different species were calculated and these fractions were multiplied with the respective woody to total area ratio of the species. To get a value for the total stand, these values were then added together.

For the correction of the needle to shoot area ratio, STAR is needed (see section 2.1). Measurements of these are not straightforward and literature values were used instead. STAR values for the pine and spruce were found in /Stenberg 1996b/. The correction factor for the needle to shoot area ratio (γ_E) was calculated with (Equation 4.) /Stenberg 1996a/. For deciduous trees, γ_E was set to one (Table 3-1). To obtain the needle to shoot area ratio of the stands, the fraction of the different species times their respective needle to shoot area ratio was calculated and added together.

The element-clumping index (Ω_E) was optically estimated with a TRAC instrument (see section 2.1). All measurements were done under bright solar conditions. In each stand, one measurement were made along five transects perpendicular to the sun. The zenith angles to the sun were between 35° and 60°. Transects were 20–35 m, depending on the size of the stand, and split up into 5 m sections.

To calculate the clumping index, the software TRACWin was used. In the calculations, woody to total area ratio, needle to shoot area ratio and mean element width (W) is needed. To estimate W, the length and diameter of ten shoots of pine, ten shoots of spruce, ten leaves of birch and ten leaves of oak were measured. W was calculated by:

$$W = \sqrt{[G(\theta)A]} \qquad \text{(Equation 6)}$$

where $G(\theta)$ is the canopy extinction coefficient, which can be approximated to be 0.5 in natural canopies, /Leblanc et al. 2002/ and A is the area of the element. In the calculation of the area of the element an approximation of leaves being circular and shoots being cylinders was made. Mean element width is given in Table 3-1. LAI (L) was then calculated using (Equation 3).

3.5 Remotely sensed data

A kNN data set /Reese 2003/ with stand volume, stand height and stand age were used for the Laxemar investigation area provided by the Swedish University of Agricultural Science, Umeå. A map covering the Laxemar investigation area describing the vegetation index NDVI derived from a SPOT image 1999-07-11 was used /Boresjö Bronge 2004/. For Forsmark, a NDVI image was produced based on Landsat 5 TM-data from 2000-06-03 (Path/row: 193/018). The satellite data was not calibrated since only relative analysis within the image were done. Uncalibrated NDVI images cannot be directly compared with NDVI images from other studies though.

NDVI was calculated according:

$$NDVI = (TM4-TM3)/(TM4+TM3) \qquad \text{(Equation 7)}$$

This fraction gives values between –1 and 1 and they were converted into positive values ranging between 0–254 by

$$NDVI_{254} = (NDVI+1)\times 127 \qquad \text{(Equation 8)}$$

Table 3-1. Parameters used for estimation of LAI. Values within the brackets were used for calculations of minimum LAI. α is woody to total area ratio, γ_E is needle to shoot area ratio and W is mean element width.

Species	α_{max} (α_{min})	γ_E	W (mm)
Pine	0.14	1.70	71.4
Spruce	0.17	1.33	47.1
Birch	0.49 (1)	1.00	30.7
Deciduous	0.25 (1)	1.00	43.8

The Forsmark NDVI image was geometrically corrected to the Swedish coordinate system Rikets nät-RT 90. Control points were collected from a cadastral map (fastighetskartan) and coordinates of investigation stands. In total 25 points from the whole investigation area were collected, for example road crossings, buildings, canals, islands and investigation stands. The first-degree polynomial transformation was used to describe the relation between the two coordinate systems. The error in fitting between the coordinate systems cannot be more than half the size of a pixel /Campbell 2002/. Landsat TM data is 30×30 m^2, and the root mean square (RMS) is therefore not allowed to be larger than 15 m. The RMS error was 9.75 m, i.e. about one third of a pixel. To get the values from the uncorrected image to the corrected image a resampling was done. The method used was cubic convolution resampling were a weighed average of values on a distance of two pixels is calculated; normally this is a weighed average over sixteen pixels.

NDVI images were stratified to different vegetation types by using a vegetation map from /Boresjö Bronge and Wester 2003/ for Laxemar and in Forsmark, a /Boresjö Bronge and Wester 2003/ vegetation map together with a cadastral map were used. Layers with coniferous forests, deciduous forests, mixed forests, open areas and water areas were created. NDVI values were assigned to the different layers.

With Arcview GIS 3.3, stand volume, stand height and stand age were extracted from the kNN data set for investigated stands in Laxemar. The NDVI values were extracted for the investigated stands in both Laxemar and Forsmark. The pixels of both the kNN (625 m^2) and the NDVI images (400 and 900 m^2) were approximately of the same size as the measured stands and no merging of pixels was therefore done.

3.6 Statistics

SPSS 12.0.1 for windows was used for the statistical analysis. First, all SKB stands (Table 4-1) measured both in Forsmark and in Laxemar were clumped and split into three groups, all stands, homogenous coniferous stands and homogenous deciduous stands. Only the SKB stands were used, since new forest inventories only had been done in these. To confirm that data was normally distributed, One-Sample-Kolmogorov-Smirnov tests were done. Data was parametric and multiple linear regressions were done with maximum LAI against measured basal area, breast height diameter, tree height, tree volume and stand breast height age. For deciduous stands, it was not possible to use regressions against volume since too few data existed.

Then both the SKB stands and the NFI stands in Laxemar and in Forsmark, were separated into four groups: all stands, homogenous coniferous stands, homogenous deciduous stands and mixed stands. One-Sample-Kolmogorov-Smirnov tests confirmed that data were parametric. In Laxemar, multiple linear regressions between LAI and the kNN dataset with stand volume, stand height and stand age were computed. It was done for minimum effective LAI, maximum effective LAI, minimum LAI and maximum LAI, but only for Laxemar since it was the only site where kNN data were available. To test if there were any correlations between minimum and maximum LAI and NDVI, and between minimum and maximum effective LAI and NDVI, curve estimations were done. For minimum LAI, only coniferous stands were tested, since they are the only tree species that are evergreen. Seven different curve estimation models were used, linear, logarithmic, power, compound, s-curve, growth and exponential regression models.

3.7 NDVI modelled LAI

For Laxemar, the best regressions from the curve estimations with LAI against NDVI for homogenous coniferous stands, homogenous deciduous stands and mixed stands were used on their respective NDVI data set. The different layers were added together and a LAI image over Laxemar was created.

For Forsmark, there were no significant relationships between LAI and NDVI when the stands were split into coniferous, deciduous and mixed forest stands, but when all stands were included there was a trend relationship between effective LAI and NDVI. Effective LAI was predicted by using this regression against NDVI. To estimate LAI, average woody to total area ratios, average needle to shoot area ratios and average element-clumping indexes were calculated for the deciduous, the coniferous and the mixed stands (Table 3-2). These values were used in (Equation 3) together with each vegetation type layer of effective LAI to create a LAI image for Forsmark.

3.8 Measured LAI versus MODIS estimated LAI

For both investigation areas, MODIS LAI coverage (collection 4) were extracted from band 2 of MODIS 15a2 the 26th of June to 3rd of July 2005. First MODIS data were geometrically corrected to the Swedish coordinate system, Rikets nät RT 90. Control points were collected from the NDVI images and sea and lake coastlines from a map over Sweden. In total 25 control points were collected and they were spread out over the investigation areas. The first order polynomial transformation was used to describe the relationship between the coordinate systems. The root mean square error was calculated to be 233 m for both Laxemar and Forsmark, i.e. about one fourth of a pixel. A cubic convolution resampling was done. All pixels within a distance of two pixels from water and other pixels given special values were removed from the rest of the analysis.

MODIS estimated LAI was compared to NDVI modelled LAI by recalculating NDVI modelled LAI to 1 km resolution by averaging the LAI values within each MODIS pixel. In the calculations, LAI of water and open areas were given a value of zero. Then, a One-Sample-Kolmogorov-Smirnov test was done to see if the data sets were normally distributed. Data was parametric in Forsmark but in Laxemar it was not even after a logarithmic transformation. A linear regression between NDVI modelled LAI and MODIS LAI was done for Forsmark while a Spearman rank correlation was done for Laxemar.

Table 3-2. Parameters used to correct effective LAI for Forsmark with Equation 3. α is woody to total area ratio, γ_E is needle to shoot area ratio and Ω_E is element-clumping index.

Stands	α	γ_E	Ω_E
Coniferous	0.19	1.38	0.88
Deciduous	0.49	1.04	0.82
Mixed	0.28	1.27	0.86

4 Results

4.1 The forest inventory

On average there were 650 stems ha^{-1} in Laxemar, while in Forsmark there were 1,820 stems ha^{-1}. The relascope measurements done in the stands gave average basal area values of 19.1 m^2 ha^{-1} in Laxemar and 20.0 m^2 ha^{-1} in Forsmark. The average breast height diameter in Laxemar was 28.0 cm and 27.3 cm in Forsmark. The tree height in Laxemar was on average 17.2 m and 18.9 m in Forsmark. The average volume of the nine stands measured in Laxemar was 162 m^3 wood ha^{-1} and for the three stands measured in Forsmark it was 226 m^3 wood ha^{-1}. Finally, the average stand breast height age was 88 years in Laxemar and 78 years in Forsmark. Results from the inventory for all stands can be seen in Table 4-1.

4.2 The optical measurements of LAI

In Laxemar, the average element-clumping indexes were 0.90 for coniferous stands, 0.83 for the deciduous stands and 0.84 for the mixed stands. Average minimum effective LAI were 1.74 for coniferous stands, 0.79 for deciduous stands and 1.28 for mixed stands. Average maximum effective LAI were 2.64 for coniferous stands, 2.70 for deciduous stands and 2.52 for mixed stands. Minimum LAI was 2.54 for coniferous stands, 0.02 for deciduous stands and 0.87 for mixed stands and finally maximum LAI was 3.94 for coniferous stands, 2.32 for deciduous stands and 2.89 for mixed stands. The result for all stands can be seen in Table 4-2.

Table 4-1. Forest inventory of SKB sites in Laxemar and in Forsmark. Basal area is m^2 ha^{-1}, no of stems is stems ha^{-1}, breast height diameter and height in meters, volume is m^3 wood ha^{-1} and stand breast height age is in years. Missing data means that no measurements were done or that volumes could not be calculated. The sites with F1 are from Forsmark while the others are in Laxemar.

Site	SKB ID-code	Basal area	No. of stems	Breast height diameter	Tree height	Stand volume	Stand breast height age
LÖV 1	ASM001426	15.0	200	0.36	17.1	158	111.5
LÖV 2	ASM001427	19.5	1,000	0.40	19.4	–	132.5
ÅS 1	ASM001424	17.5	1,100	0.28	16.9	140	116.0
ÅS 2	ASM001425	22.0	600	0.25	13.7	144	80.0
SUMP 1	ASM001434	17.5	1,600	0.14	11.6	41	41.5
SUMP 2	ASM001435	11.0	600	0.19	17.5	–	37.5
GRAN 1	ASM001440	15.5	400	0.32	21.0	152	55.0
GRAN 2	ASM001441	34.5	500	0.35	26.6	431	48.5
VH 1	ASM001432	12.0	400	0.24	12.1	71	130.5
VH 2	ASM001433	20.5	400	0.22	13.3	133	122.5
TALL 1	ASM000211	20.0	–	–	–	–	–
LAV	ASM000210	22.5	–	–	–	–	–
HÄLL	ASM001429	21.0	300	0.33	19.6	185	96.0
LÖV FL2	AFM001071	13.5	–	0.32	21.5	–	77.5
SUMP SS1	AFM001076	16.5	3,340	0.29	18.1	230	89.5
GRAN FG1	AFM001068	27.5	780	0.27	19.8	264	84.5
TALL B2a	AFM001247	22.5	1,340	0.21	16.3	185	59.5

Table 4-2. Element-clumping index, effective LAI and LAI for Laxemar. In the tree category column, P means homogenous pine stand, P, S means homogenous coniferous stand mixed with pine and spruce, M means mixed coniferous and deciduous stand, D means homogenous deciduous stand and S means homogenous spruce stand. Ω_E is the element-clumping index, min and max L_e, is minimum and maximum effective LAI and min and max LAI is minimum and maximum LAI.

Site	SKB ID-code	Tree category	Ω_E	L_e (min)	L_e (max)	LAI (min)	LAI (max)
NFI 1	ASM000078	P	0.84	1.48	1.7	2.59	2.98
NFI 2	ASM000079	P, S	0.89	–	2.55	–	3.61
NFI 3	ASM000080	P	0.88	1.19	2.47	1.99	4.13
NFI 4	ASM000081	M	0.89	2.47	3.14	1.10	3.14
NFI 5	ASM000082	M	0.84	1.55	1.26	1.63	1.85
NFI 6	ASM000083	P	0.83	1.39	2.13	2.15	3.51
NFI 7	ASM000084	P	0.97	2.41	3.64	3.64	5.51
NFI 8	ASM000085	P	0.96	1.67	2.53	2.55	3.87
NFI 9	ASM000086	B	0.80	1.14	2.52	0.08	1.76
NFI 10	ASM000087	M	0.75	1.13	1.88	0.97	2.38
NFI 11	ASM000088	P	0.92	1.49	3.3	2.25	5.00
NFI 12	ASM000089	D	0.81	1.02	3.23	0.00	3.01
NFI 13	ASM000090	M	0.83	1.04	3.15	0.52	3.28
NFI 14	ASM000091	P	0.97	–	3.74	–	5.60
NFI 15	ASM000092	P	0.98	1.01	2.38	1.51	3.56
NFI 16	ASM000093	M	0.90	0.23	3.19	0.14	3.78
NFI 17	ASM000094	S	0.97	3.84	5.02	3.93	5.50
NFI 18	ASM000095	B	0.84	0.62	0.93	0.02	0.38
NFI 19	ASM000096	P	0.86	2.34	4.17	3.34	6.50
NFI 20	ASM000097	P	0.98	2.26	3.86	3.17	5.63
NFI 21	ASM000098	D	0.84	0.53	3.7	0.01	3.80
LÖV 1	ASM001426	D	0.80	0.61	1.85	0.00	1.55
LÖV 2	ASM001427	D	0.94	0.88	5.23	0.00	4.63
ÅS 1	ASM001424	P	0.91	1.15	1.75	1.79	2.76
ÅS 2	ASM001425	P	0.90	1.24	1.54	2.03	2.52
SUMP 1	ASM001434	D	0.93	0.76	2.06	0.03	1.44
SUMP 2	ASM001435	B	0.68	0.72	2.06	0.00	1.97
GRAN 1	ASM001440	S	0.92	2.34	3.00	2.79	3.58
GRAN 2	ASM001441	S	0.89	2.66	3.53	3.22	4.31
VH 1	ASM001432	P	0.90	1.19	1.34	1.95	2.19
VH 2	ASM001433	P	0.86	1.31	1.57	2.24	2.69
TALL 1	ASM000211	P	0.99	1.49	1.73	2.21	2.57
LAV	ASM000210	P	0.74	1.34	1.8	2.59	3.47
HÄLL	ASM001429	P	0.79	1.23	1.72	2.29	3.20

In Forsmark, average element-clumping index were 0.88 for coniferous stands, 0.82 for deciduous stands and 0.86 for mixed stands. Average minimum effective LAI were 2.19 for coniferous stands, 1.47 for deciduous stands and 2.19 for mixed stands. Average maximum effective LAI were 2.97 for coniferous stands, 3.06 for deciduous stands and 3.23 for mixed stands. Minimum LAI were 2.68 for coniferous stands, 0.17 for deciduous stands and 2.37 for mixed stands and at last maximum LAI were 3.84 for coniferous stands, 2.04 for deciduous stands and 3.43 for mixed stands in Forsmark. Results of the optical measurements for all stands in Forsmark can be seen in Table 4-3.

Table 4-3. Element-clumping index, effective LAI and LAI for Forsmark. In the tree category column, M means mixed coniferous and deciduous stand, S means homogenous spruce stand, B, D means homogenous deciduous stand mixed with birch and deciduous trees, P means homogenous pine stand, S, P means homogenous coniferous stand mixed with spruce and pine trees and D means homogenous deciduous stand. Ω_E is the element-clumping index, min and max L_e is minimum and maximum effective LAI and min and max LAI is minimum and maximum LAI.

Site	SKB ID-code	Tree category	Ω_E	L_e (min)	L_e (max)	LAI (min)	LAI (max)
NFI F1	AFM001316	M	0.77	1.84	2.5	1.52	2.82
NFI F2	AFM001317	S	0.93	2.13	2.99	2.54	3.57
NFI F3	AFM001318	B, D	0.78	1.97	2.95	0.02	1.26
NFI F4	AFM001319	M	0.77	2.41	2.91	2.66	4.17
NFI F5	AFM001320	M	0.93	1.93	3.77	0.94	3.30
NFI F6	AFM001321	S	0.89	2.32	4.13	2.86	5.09
NFI F7	AFM001322	P	0.95	1.4	2.63	2.13	4.01
NFI F8	AFM001323	B, D	0.93	1.27	3.18	0.36	2.25
NFI F9	AFM001324	S	0.86	1.7	2.64	2.16	3.36
NFI F10	AFM001325	M	0.9	2.21	3.48	1.60	3.90
NFI F11	AFM001326	S, P	0.67	2.13	3.24	3.90	5.93
NFI F12	AFM001327	M	0.94	2.54	3.47	1.39	2.94
NFI F13	AFM001328	S	0.91	2.17	2.25	2.69	2.80
NFI F14	AFM001329	S, P	0.97	2.32	2.55	2.34	2.88
LÖV FL2	AFM001071	D	0.74	1.18	3.05	0.15	2.62
SUMP SS1	AFM001076	S, P	0.93	2.41	3.24	2.24	3.50
GRAN FG1	AFM001068	S	0.90	2.38	2.71	2.13	2.87
TALL B2a	AFM001247	S	0.81	2.92	3.31	3.85	4.42

4.3 The effects of stand characteristics on LAI

Multiple linear regressions between LAI and the stand characteristics did not explain maximum LAI better than single factor regressions did, adding the effect of the factors together does not give a better explanation than the factors did by themselves. As single factor regressions, basal area height and volume affected maximum LAI positively. For breast height diameter there was a positive trend relationship. Separating the coniferous and deciduous stands, did not give LAI stronger relationships to any of these stand characteristics, i.e. the coniferous and deciduous stands have the same relationship to these factors. When it comes to age, maximum LAI of the coniferous and deciduous stands have different relationships; no significance could be found for all stands, but when separated, a clear linearly negative relationship was seen for coniferous stands. For deciduous stands, no relationship could be statistically detected. For regression statistics, see Table 4-4.

Table 4-4. Relationships between stand characteristics and LAI of SKB stands. All equations follow the form L = *k*x+b, where L is maximum LAI and x is the stand character.

Stand character	Stands	d.f.	b	*k*	F-value	*p*-value	R^2
Basal area	All	15	1.2883	0.0864	5.86	0.029	0.28
Height	All	13	0.4327	0.1428	6.38	0.025	0.33
Volume	All	10	1.7712	0.0065	8.69	0.015	0.47
Breast height diameter	All	13	1.064	0.0681	3.97	0.068	0.23
Age	Coniferous	8	5.0671	–0.0212	15.81	0.004	0.66

4.4 The relationship between satellite derived information and LAI

Even if LAI is related to the stand characteristics, no significant relationships could be found between LAI and stand volume, stand height and stand age from the kNN data set. There were no significant correlations with either multiple or single factor linear regressions.

In Laxemar, there were no significant relationships for maximum LAI of all stands against NDVI. Several significant curve estimation models predicting maximum effective LAI could be seen and the logarithmic regression gave the best explanation (*p*-value 0.000; R^2 0.325). There was a big difference for coniferous and deciduous stands in their relationship to NDVI since when separating the stands into coniferous, deciduous and mixed, clear relationships between maximum LAI and NDVI were found. For the coniferous stands, the best-fit curves were exponential, compound and growth functions, for deciduous it was the S-curve and for mixed stands there was only a trend relationship and it was linear (Table 4-5). For the coniferous stands the exponential regression were chosen for further analysis. There were also significant relationships between NDVI and maximum effective LAI for coniferous (linear regression; *p*-value 0.000; R^2 0.586), mixed (linear regression; *p*-value 0.063; R^2 0.736) and deciduous (exponential regression; *p*-value 0.011; R^2 0.684) forest stands. The variation in maximum effective LAI is better explained than the variation in maximum LAI for the coniferous and the mixed forest stands, while it is the opposite for the deciduous stands. For the coniferous stands, linear regressions against NDVI were the best models to explain both minimum LAI (*p*-value 0.013; R^2 0.314) and minimum effective LAI (*p*-value 0.002; R^2 0.425).

In Forsmark, no relationships could be found between maximum LAI and NDVI, even when stands were separated into different groups. For all stands, a trend relationship was detected for the regression with maximum effective LAI against NDVI. The best regressions were compound, exponential and growth functions (*p*-value 0.065; R^2 0.197) (Table 4-5). The Exponential were chosen for further analysis. No relationships for minimum LAI and minimum effective LAI of the coniferous stands with NDVI was detected for Forsmark.

4.5 NDVI modelled LAI

The NDVI modelled LAI ranges from 0.00–9.52 with a mean of 3.45 for the forests in Laxemar and it ranges from 0.99–4.93 with a mean of 3.58 in Forsmark. For NDVI modelled LAI in Laxemar see Figure 4-1. and for NDVI modelled LAI in Forsmark see Figure 4-2.

Table 4-5. Maximum LAI of Laxemar and maximum effective LAI of Forsmark against NDVI. Equations follow the form $L = be^{k(N)}$ for coniferous stands in Laxemar, $L = e^{(b+k/(N))}$ for deciduous stands in Laxemar and $L = k(N)+b$ for mixed stands in Laxemar. For all stands in Forsmark, the equation is $L_e = be^{k(N)}$. In the equations L is maximum LAI, N is NDVI and L_e is maximum effective LAI. These equations can only be used against the NDVI datasets of SPOT, 1999-07-11, for Laxemar and Landsat 5, 2000-06-03, for Forsmark, since images were analysed without calibration.

Stands	Site	d.f.	b	*k*	F-value	*p*-value	R^2
Coniferous	Laxemar	19	0.383	0.017	20.4	0.000	0.52
Deciduous	Laxemar	6	6.942	–1,025.023	19.94	0.004	0.77
Mixed	Laxemar	3	–1.115	0.025	5.73	0.097	0.66
All	Forsmark	16	0.881	0.007	3.94	0.065	0.20

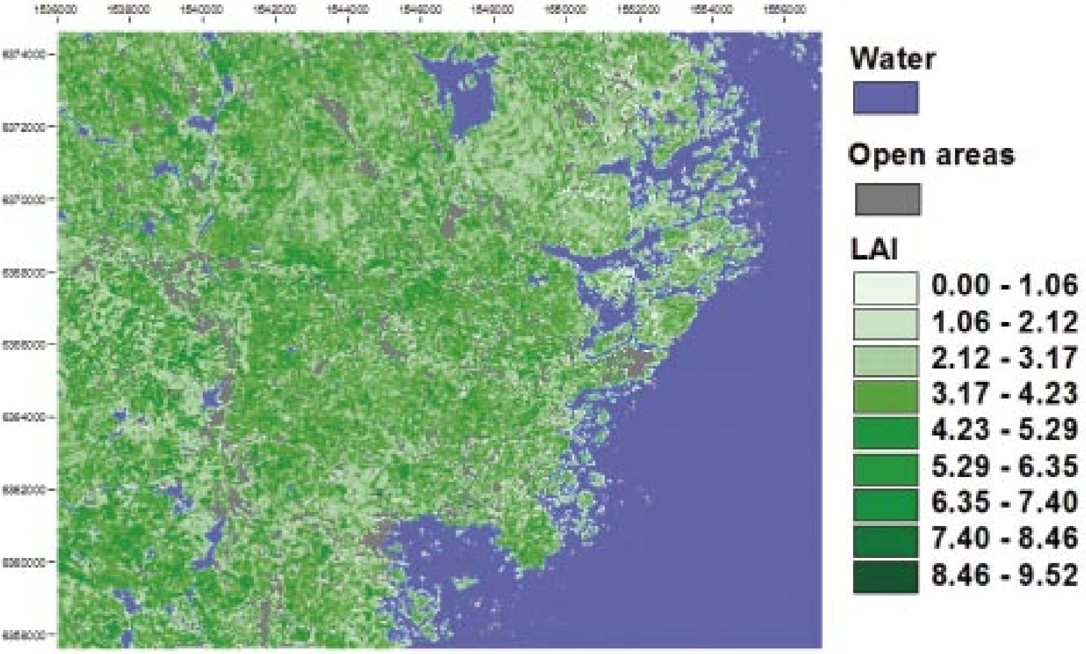

Figure 4-1. *NDVI modelled LAI for the Laxemar investigation area.*

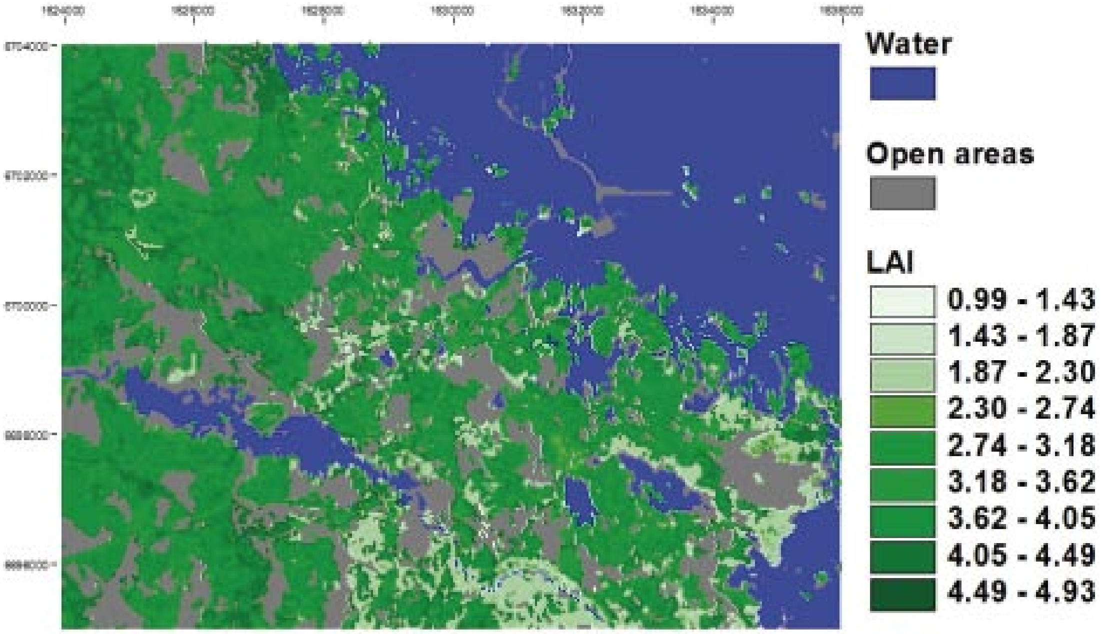

Figure 4-2. *NDVI modelled LAI for the Forsmark investigation area.*

4.6 MODIS evaluation

MODIS estimated LAI values were both higher and showed a larger variance than NDVI modelled LAI did (Figure 4-3). Average MODIS LAI in Laxemar was 4.77 and in Forsmark it was 5.16. For the same pixels, average NDVI modelled LAI was 2.91 for Laxemar and it was 3.02 for Forsmark. The linear regression for Forsmark indicated that there was no relationship between MODIS LAI and NDVI modelled LAI (*p*-value 0.95; R^2 0.00). The Spearman rank correlation test for Laxemar did not indicate any significant correlation (d.f. = 207, correlation coefficient = 0.592, p = 0.59) between MODIS LAI and NDVI modelled LAI.

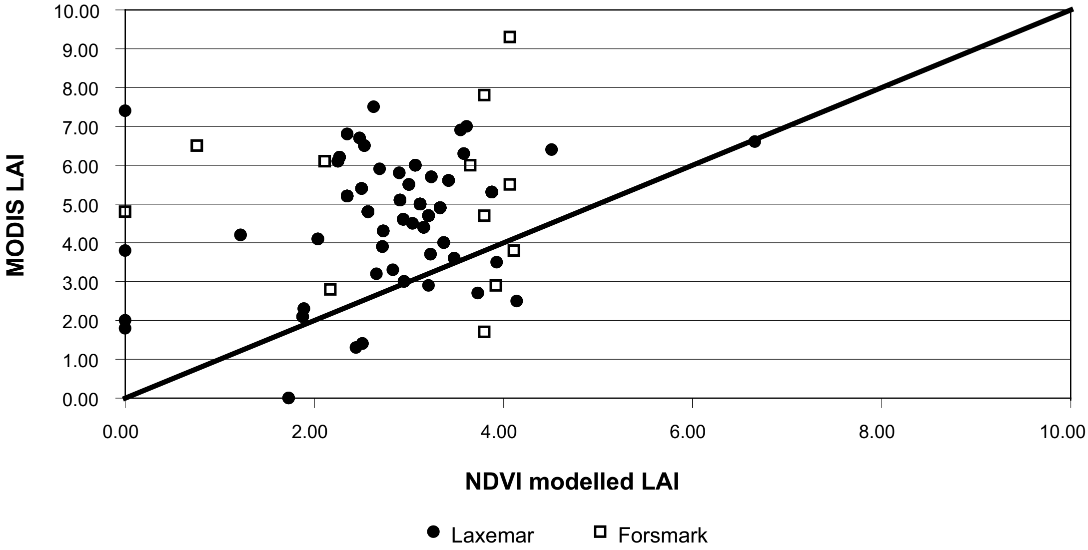

Figure 4-3. *MODIS LAI against NDVI modelled LAI for Laxemar and Forsmark. The thick line is the one to one theoretical relationship.*

5 Discussion

5.1 Forest inventory

In Laxemar, the stem density in each of the stands is only indicative since only one estimate per stand was done. The average value calculated for the whole Laxemar investigation area is less prone to errors since this is an average from a larger sample. This is the reason that stems were counted in five circles per ecosystem in the Forsmark investigation area. The same problem does not exist for the basal area measurements since a large number of trees are counted when using a relascope and the measurement were repeated to ensure that a mean value for the entire stand was estimated. Height and breast height diameter was measured for ten trees, a relatively large fraction of the total amount of trees from the stand. Average volume of forests in Sweden is 127 m^3 wood ha^{-1} /Swedish statistical year book of forestry 2005/. In Uppsala county the average volume is 167 m^3 wood ha^{-1} and in Kronoberg county it is 183 m^3 wood ha^{-1}. The stands measured in Forsmark (226 m^3 wood ha^{-1}), have a slightly larger amount wood while the stands in Laxemar (162 m^3 wood ha^{-1}) has a slightly smaller amount of wood compared to forests in their regions. The SKB stands are old (85 years) compared to the forests of Kronoberg county and Uppsala county, with an average age of 48 years.

5.2 Optical measurements

Previous comparative studies have shown that optical methods are reliable and can be used to estimate LAI /Chen 1996, Chen et al. 1997, Gower et al. 1999, Eriksson et al. 2005/. An error analysis performed by /Chen 1996/ indicated that optically measured LAI has an accuracy of between 15 and 40%. 3–5% of the error origins from the LAI-2000 measurements, 3–10% from the element-clumping index estimations, 5–10% from the needle to shoot area ratio and 5–10% from the woody to total area ratio.

Caution should also be taken to direct destructive methods, the error analysis performed by /Chen 1996/ indicated that in coniferous stands, optically based methods can, if performed correctly, give even more accurate results than direct destructive methods. Both /Eriksson et al. 2005/ in deciduous stands and /Law et al. 2001/ in coniferous stands had problems with their direct estimations from litter traps, the main problems were differences in specific LAI from leaves picked from upper and lower positioned branches, annual changes in climatic factors and scaling issues. For direct destructive methods to be reliable, and to be able to validate the optically measured LAI, at least ten trees of the different species has to be cut, all shoots clipped, all needles measured and allometric equations developed /Chen 1996, Gower et al. 1999/. These allometric equations are also site specific and can only be used in the same stand as where the measurements were done /Chen 1996, Gower et al. 1999/.

There are problems with the optical measurements as well, mainly arising from the assumptions of the correction factors due to clumping of the foliage and the woody to total area ratio /Weiss et al. 2004/. The correction factors used in the equation to correct effective LAI are not universal and should be measured in each of the stands were LAI is to be corrected /Stenberg 1996a/. Alternative methods for correction of effective LAI have been suggested, but none have been really successful. /Nilson 1999/ used stand characteristics in gap fraction formulas to estimate LAI, but these estimations are not as easily done, since they require knowledge about the canopy structure. New theories are under development since the introduction of high-resolution hemispherical digital cameras making sampling much easier and more accurate. In the future they might result in more correct estimations of LAI /Weiss et al. 2004/.

In this study, it was not possible to do estimation of all correction factors for each stand because of limited resources and the destructive manner of the estimation techniques. A species-specific needle to shoot area ratio found in the literature was therefore used and the only other factor accounted for between the stands was species composition. It should be mentioned that needle to shoot area ratio differs also due to other factors such as environmental conditions, fertilization, competition for sunlight and latitude /Stenberg et al. 1995, Stenberg 1996b/. Literature values were also used for the woody to total area ratios. It has the same problem as the needle to shoot area ratio and for better corrections, a woody to total area ratio should have been estimated for each stand where LAI was estimated /Stenberg 1996b, Weiss 2004/. This could have affected LAI and given it an incorrect value, but according to /Chen et al. 1997/, there is not much variation in these factors once the stands have become mature, which justifies the use of average values.

There are also uncertainties regarding the estimation technique for deciduous woody to total area ratio. Leaves cover the branches that they grow upon and when estimating woody to total area ratio by LAI-2000 estimates in April divided by LAI-2000 estimates in June, the influence of the shading of the branches should be excluded /Kucharik 1998, Gower et al. 1999/. However, /Eriksson et al. 2005/ showed that LAI estimated when branches were included gave better results than when using only the stem area index. New methods involving hemispherical digital photographs, where wavebands with green and non-green materials are separated, is now developed for a non-destructive estimate of the woody to total area ratio /Weiss et al. 2004/. The best would be if this method were used for each stand where LAI were estimated.

5.3 The effects of stand characteristics on LAI

Structural factors such as basal area, tree diameter, tree height and tree volume of the stand, naturally affect the space available for canopy and therefore also affects the LAI of the stands. Tree diameter, furthermore, affects LAI as an increased diameter increases the water conductivity of the trees and it is not uncommon that water is a limiting factor in green leaf production /Le Dantec et al. 2000/.

The different relationships of LAI with age for deciduous and coniferous stands are probably due to different maturity of the stands; all coniferous stands had reached a mature state while the deciduous stands had not. LAI respond differently to age at different periods of their life cycle /Kashian et al. 2005/. The decline in LAI for the coniferous stands when ageing has been seen in earlier studies of mature stands as well /Gower et al. 1996, Binkley et al. 2002, Kashian et al. 2005/. /Gower et al. 1996/ explain a decrease in aboveground net primary production by decreasing soil nutrient availability and increasing hydraulic resistance in the stomata, which decreases water conductivity. /Binkley et al. 2002/ explain the decline in forest growth by competition related changes in stand structure, where fewer large dominant trees sustain their resource efficiency at a cost of the resource efficiency of smaller non-dominant trees. /Smith and Long 2001/ has a similar explanation; the decline in forest growth is a result of canopy closure and interference between tree crowns. These factors affect production of foliage of the stands and they results in a decrease in basal area and volume of the stands with age /Smith and Long 2001, Binkley et al. 2002, Kashian et al. 2005/.

5.4 The relationship between satellite derived information and LAI

The analysis with the kNN dataset against LAI indicated that the kNN dataset is not very useable for regional extrapolation of LAI. LAI was correlated to measured volume, height and age, but still there were no correlations to the kNN dataset with the same stand characteristics.

Not even regression analysis between measured volume and kNN volume, measured height and kNN height, and between measured age and kNN age did show any significant correlations. The explanation to the fact that the kNN dataset did not show any relationship is that the kNN dataset is not proper to use at this small scale; the accuracy of a pixel value is low, but increases on a regional scale /Reese et al. 2003/. The kNN data set should instead be used as average values for larger areas /Reese et al. 2003/.

Previous studies have shown that the relationships between NDVI and LAI are site specific and differ with vegetation type /Myneni et al. 1997b, 2002, Nilson et al. 1999, Turner et al. 1999, Eklundh et al. 2001, Stenberg 2004, Yao et al. 2005/. Another factor that affects reflectance of radiation and NDVI of stands are ground vegetation /Nilson et al. 1999/. In this study, several curve estimation models were tested and the regressions that best explained LAI were of an exponential character for coniferous and deciduous stands, while it was linear for mixed stands in Laxemar. Because of differences in canopy structures, NDVI is lower for coniferous forests than for deciduous forests while LAI is slightly larger for coniferous forests than for deciduous forests. The mixed stands are in between these and hence show a linear relationship (Figure 5-1).

In Forsmark, there was no correlation between LAI and NDVI when the coniferous, deciduous and mixed stands were separated, since too few measurements were done. Measurements of effective LAI do no differ between coniferous and deciduous stands as they are simply based on the radiation transmission through the canopy /Chen et al. 1997/. Therefore, for all stands effective LAI was correlated to NDVI, while LAI was not. NDVI is mostly influenced by green leafy material /Turner et al. 1999/, and when separating LAI into coniferous, deciduous and mixed, it should give a better relationship than for effective LAI in all stands, since woody materials also influences effective LAI. For deciduous stands, LAI had the best correlations to NDVI, while the coniferous stands were better correlated to effective LAI. The main explanation is probably the problems with the correction factors for the coniferous stands. Still, there is a strong correlation for LAI of coniferous stands to NDVI and this indicates that the correction factors are correct within reasonable limits.

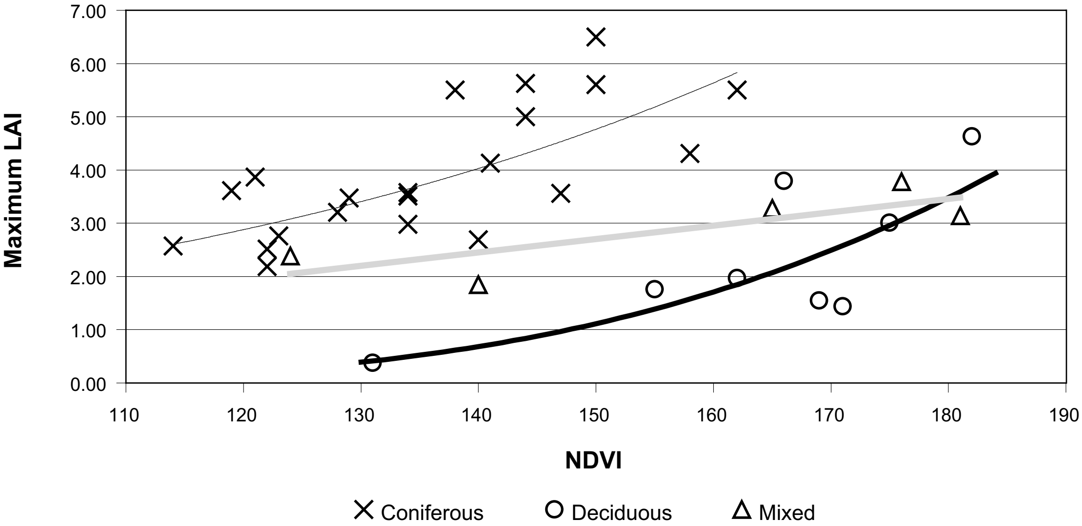

***Figure 5-1**. Maximum LAI against NDVI for the different vegetation types in Laxemar. The thin line are the exponential regression between maximum LAI and NDVI for the coniferous forest stands, the shaded line is the linear regression between maximum LAI and NDVI for the mixed forest stands and the thick line is the S-curve for the deciduous forest stands. For statistics of the regression see Table 4-5.*

Moreover, the correction factors of coniferous stands must affect LAI differently in different NDVI ranges as the best regression fit changed from being linear for effective LAI to being exponential for LAI. It could be that the element-clumping index changes due to how dense the stand is /Law et al. 2001/ or that species fraction (included in woody to total area ratio, needle to shoot area ratio and element-clumping index) affects differently in different NDVI ranges (Figure 5-1).

Minimum LAI can only be analysed for coniferous trees since they are the only ones that are evergreen. The NDVI images are from June, when deciduous trees also have leaves in the mixed forest stands. To be able to extrapolate minimum LAI it is necessary to use NDVI images from around April. In Forsmark, there were no significant relationships for minimum LAI, since too few stands were analysed.

5.5 NDVI modelled LAI

It is not possible to evaluate the NDVI modelled LAI with independent LAI measured values. Too few measurements were done to separate some to be used in an evaluation. Average LAI is realistic for both sites compared to other studies /Stenberg et al. 1994, 2004, Chen et al. 1997, Gower et al. 1999, Kollenberg and O’Hara 1999, Turner et al. 1999, Le Dantec et al. 2000, Leblanc and Chen 2001, Weiss et al. 2004/. The LAI range is reasonable for Forsmark, while LAI values up to 9.52 for Laxemar is high compared to other studies /Stenberg et al. 1994, 2004, Chen et al. 1997, Gower et al. 1999, Turner et al. 1999, Le Dantec et al. 2000, Leblanc and Chen 2001, Weiss et al. 2004/. Even if 9.52 is high, it is not that much higher than other studies and /Turner et al. 1999/ reported LAI up to about 13. The main explanation to the large range of LAI in Laxemar is probably an erroneous vegetation map. At some stands, where the vegetation map in Laxemar indicates that there should be coniferous forest there are deciduous forests. Deciduous forests have larger NDVI, and when the exponential regression for coniferous forests is used on these large NDVI values, a too high LAI value is estimated. The vegetation map used in the LAI analysis should be used with caution according to /Boresjö Bronge and Wester 2003/ and since the LAI images are based on these vegetation maps, it is also necessary to be careful with the LAI images.

In the LAI image for Forsmark, effective LAI was modelled for all stands and there was no separation between the different species. Since there was no separation between the species it did not matter what type of forest there was in the estimates of effective LAI and the land cover of the vegetation map could not be wrong classified. Large NDVI values as a result of misclassification did hereby not result in large LAI values in the Forsmark LAI image, as it did in the Laxemar LAI image. In Forsmark, the range is quite small and this could be explained by low R^2-values. With a low explanation of the variation, the model gets more evened out; a high LAI value is lowered and a low LAI values is increased. Another explanation to the low range in Forsmark is that the same correction factors are used for all pixels with similar land cover class for the entire image, lowering the possible range of LAI values for the stands. Still, the ranges at both sites is not totally unrealistic and they are both reasonable compared to former studies /Stenberg et al. 1994, 2004, Chen et al. 1997, Gower et al. 1999, Kollenberg and O’Hara 1999, Turner et al. 1999, Le Dantec et al. 2000, Leblanc and Chen 2001, Weiss et al. 2004/.

Another problem with the vegetation mapping is that it does not cover the total area in Forsmark. For about 30 percent of the vegetation stratification, a cadastral map (fastighetskartan) is used instead. This part is not over the inner Forsmark investigation area and as long as it is only the investigation area that is of interest it does not matter. The cadastral map does not separate mixed and coniferous forests and these areas are all modelled as coniferous.

5.6 MODIS comparison

There are two main problems with the MODIS comparison. Firstly, the MODIS images and the Landsat and SPOT developed images are not from the same date. MODIS data started to be available in 2001 and the NDVI images from Landsat and SPOT are from 2000 and 1999. Therefore, MODIS data from end of June 2005, when the field measurements were made, were used instead. Also, MODIS data are not accurate on a pixel level, but to be used on a larger scale /Wang et al. 2004/. In validation of MODIS images, a larger regional approach would be preferable, where average values of several regions could be calculated and evaluated.

MODIS has set the accuracy of their product to be 0.5 LAI /Wang et al. 2004/, but this is exceeded at both sites; on average MODIS overestimates LAI with 1.86 in Laxemar and 2.14 in Forsmark. An overestimation by MODIS LAI is also seen in earlier studies /Cohen et al. 2003, Wang et al. 2004/. Several things could explain overestimations in LAI by MODIS. The MODIS algorithm is adjusted to a high resolution and it therefore generally overestimates LAI due to influences from the under storey vegetation /Wang et al. 2004/. The LAI algorithm therefore needs to be improved. Another problem could be biome misclassification due to the large pixel size for MODIS LAI /Myneni et al. 2002, Verbyla 2005/. In MODIS, the entire pixel is set to have the same biome class, while in the investigation areas there are mixtures of vegetation. In the NDVI model, there are for example open areas, given a LAI value of zero, and these naturally lower LAI in comparison to MODIS, which expects forests over the entire pixel. /Cohen et al. 2003/ suggested another reason for MODIS overestimation of LAI in their study, namely that the algorithm is strongly dependent on the red and near infrared bands. An improvement could be to incorporate additional MODIS bands into the algorithm /Cohen et al. 2003/.

Another problem with the MODIS estimated LAI is the large scatter seen in Figure 4-3, which is not found in the NDVI estimated LAI. The reasons for this could be the shortages in the LAI algorithm, but also uncertainties in the reflectance from the atmosphere, that could affect differently in different parts of the image /Wang et al. 2004/. Other explanations are that the understorey affects differently for different parts of the image because of various factors such as soil texture and microclimate and that the image has such a coarse resolution that the mixture of vegetation affects differently in different pixels /Myneni et al. 2002, Wang et al. 2004, Verbyla 2005/.

5.7 Conclusions

On average, maximum LAI was 3.40 in Laxemar and it was 3.43 in Forsmark, while minimum LAI was 1.65 for Laxemar and it was 1.97 for Forsmark. Basal area, stand height, stand volume, breast height diameter and stand age affected LAI and they explain the spatial variation in LAI between the stands. There is no significant relationships for LAI to the satellite derived kNN data set with stand height, stand volume and stand age even if these stand characteristics affect LAI. The kNN data set can therefore not be used to extrapolate LAI over the investigation areas. LAI is correlated to NDVI in Laxemar and NDVI images can be used for extrapolation of LAI. In Forsmark, effective LAI is correlated to NDVI and a NDVI image can be used for extrapolation of effective LAI. The effective LAI image was corrected for average needle to shoot area ratio, woody to total area ratio and element-clumping index for coniferous, deciduous and mixed forest stands. The comparison between NDVI modelled LAI and MODIS LAI indicated that MODIS LAI was neither correlated to LAI in Laxemar nor in Forsmark. MODIS LAI was also larger than NDVI modelled LAI and it had large variance at both sites. It is therefore not recommended to use MODIS LAI for future estimations of LAI in these small investigation areas.

For the site characterisation by SKB of the Laxemar and the Forsmark investigation areas, these LAI estimates can be an extra tool in their ecosystem modelling. First, the correlations between LAI and stand characteristics found, can be used on the NDVI modelled LAI images for extrapolation of the stand characteristics over the entire investigation areas. Similar estimates can be done between LAI and other field investigations done in the areas. But it is not just the LAI images that can be used for spatial extrapolation of ecosystem features over the investigation areas. The direct field measured LAI estimates is also a strong tool in the ecosystem modelling as they can either be used as an input to the ecosystem models done for the investigation areas or used as values to compare with the outputs given by the models.

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