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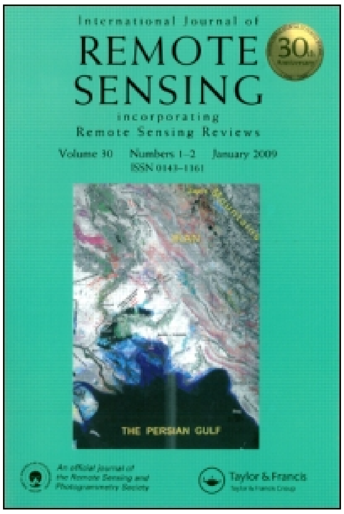

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Applicability of leaf area index products for boreal regions of Sweden

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Leaf area index (LAI) of boreal ecosystems was estimated with optical instruments at the Laxemar and the Forsmark investigation areas in Sweden. The aim was to study relationships between LAI and normalized difference vegetation index (NDVI), and to evaluate the applicability of the moderate resolution imaging spectroradiometer (MODIS) LAI product for small boreal regions. Relationships between optically-estimated LAI and NDVI were significant for different forest types in Laxemar and for Forsmark, effective LAI was correlated to the NDVI for all sites. NDVI-estimated LAI was used for evaluating accuracy of the MODIS LAI product and the comparison showed no correlation in Forsmark, whereas they were correlated in Laxemar. MODIS LAI was, on average, 2.28 higher than NDVI-based LAI, and it showed larger scatter. Scale issues were the main explanation for the high MODIS LAI, since heterogeneous landscapes with open areas were seen as forest in the large pixels of the MODIS LAI product.

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1. Introduction

Leaves are important in the exchange of matter and energy between the atmosphere and the biosphere, and leaf area index (LAI) of the vegetation cover is an important variable in the study of global carbon budgets (Chen *et al.* 1997). The LAI is used for quantifying and up-scaling physiological processes, such as photosynthesis, productivity and transpiration, and is closely linked to other ecosystem features, such as litter fall, root production, nutrient availability and soil respiration (Bonan 1993, Chen and Cihlar 1995, Fassnacht and Gower 1997, Jose and Gillespie 1997, Coble *et al.* 2001, Sakai and Akiyama 2005). Furthermore, the LAI responds quickly to stress factors and may also serve as an indicator of climate change (Myneni *et al.* 1997a). Here, the LAI was defined as half the total leaf area per unit of surface area (Chen and Black 1992).

It has also been shown that LAI is strongly correlated to vegetation indices, such as the normalized difference vegetation index (NDVI) (e.g. Myneni *et al.* 1995, 1997b, 2002, Nilson *et al.* 1999, Turner *et al.* 1999, Eklundh *et al.* 2001, 2006, Stenberg *et al.* 2004). Other indices and reflectances have shown even stronger correlations to LAI for boreal forests (Eklundh *et al.* 2003), but the NDVI has some advantages. Long time series of global estimates of the NDVI are easily available from the National Oceanographic and Atmospheric Administration (NOAA) satellites (1982 onwards) and the moderate resolution imaging spectroradiometer (MODIS) (2000 onwards).

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This makes it possible to study long-term variations. Furthermore, the NDVI has been found to be relatively insensitive to view-angle variations in dense forests of boreal regions (Eklundh *et al.* 2006).

The LAI, given a value between 0 and 10, is one of a number of standard products for the terrestrial surface that are available from the MODIS sensor on board the Terra (EOS AM) satellite, launched in 1999, and the Aqua (EOS PM) satellite, launched in 2002. The main advantage of the MODIS data is that it has a high temporal resolution, the MODIS covers the entire Earth every 1–2 days, and the LAI product is based on 8 day composites. The MODIS LAI product is generalized and has a spatial resolution of 1 km^2. The launch of Terra with the MODIS onboard started a new era in remote sensing, and as its products became available via the Earth observing system data gateway, the products have been widely used in many kinds of applications.

This study set out to investigate the LAI of boreal ecosystems in the Laxemar investigation area in south-eastern Sweden and in the Forsmark investigation area in central Sweden. These two areas are part of the Swedish Nuclear Fuel and Waste Management Co. (SKB) investigations for possible construction of a deep repository for the nuclear waste produced at the power plants in Sweden, and this study also forms part of these investigations (Tagesson 2006). There were two general aims. Firstly, the NDVI is a widely used vegetation index and it has been shown that the LAI and NDVI are strongly correlated (Myneni *et al.* 1997b, 2002, Nilson *et al.* 1999, Turner *et al.* 1999, Eklundh *et al.* 2001, Stenberg *et al.* 2004). We wanted to examine the relationship between the LAI and NDVI because it is commonly applied within the field of remote sensing, long time series of the NDVI exist and it is fairly insensitive to view-angle variations in the dense forests of these latitudes (Eklundh *et al.* 2006). Secondly, as the MODIS products are easily available and widely used in many applications, it is important to test the applicability and accuracy of the MODIS LAI product (Myneni *et al.* 2002, Tian *et al.* 2002). We wanted to examine and evaluate the MODIS LAI product to see if it could be used for continuous estimates of the LAI in small boreal regions such as the Laxemar and Forsmark investigation areas.

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2. Material and method

2.1 *Description of investigation areas*

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 centre of Sweden (60° 4′ N, 18° 2′ E). Both areas are situated along the coast of the Baltic Sea. Mean annual temperatures in 2005 were 7.3°C and 6.9°C in Laxemar and Forsmark, respectively, and annual precipitation in 2005 was 434 mm for Laxemar and 437 mm for Forsmark. The 2005 growing season started at the beginning of April and ended in the middle of November at both investigation areas (threshold 5°C). The Laxemar investigation area is characterised by relatively low topography and the dominant forest is Dry Scots pine (*Pinus sylvestris*) forest. However, 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. The Forsmark investigation area is also characterised by relatively low topography and is dominated by coniferous forests mixed with arable land and pastures. The dominant forests are Scots pine and Norway spruce, but deciduous forests with birch (*Betula pendula*), alder (*Alnus glutinosa*) and rowan (*Sorbus acuparia*) are also common. SKB has conducted extensive ecological, hydrological, meteorological and geological investigations at both areas (Lindborg 2005, 2006).

Sites within larger forest stands at Laxemar and Forsmark were selected for this study in two different ways. Firstly, the National forest inventory has compiled inventories in Swedish forests since 1924, and we selected sites within the investigation areas where inventories were carried out after 1990 (Skogstyrelsen 2002). We sampled 21 sites in Laxemar and 14 sites in Forsmark. Secondly, SKB had also chosen 13 representative forest sites for the Laxemar investigation area and four representative forest sites for the Forsmark investigation area to be used for their descriptions (Lundin *et al.* 2004, 2005). The sites chosen were of different vegetation types: coniferous forests, deciduous forests and mixed deciduous and coniferous forests. In total, in Laxemar, there were 21 coniferous, eight deciduous and five mixed forest sites, and in Forsmark, there were 10 coniferous, three deciduous and five mixed forest sites. The sites were classified as being homogenous or mixed, depending on whether the proportion of one single group (pine, spruce, birch or deciduous) exceeded 0.7 (Håkansson and Steffen 1994). The area of the sites varied between 400 m^2 and 1225 m^2.

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2.2 *Optically based estimates of LAI*

The LAI was estimated using the gap-fraction method, where LAI was estimated from:

$$L = L_e\,(1-\alpha)\gamma_E/\,(\Omega_E), \tag{1}$$

where L is the LAI; L_e is the effective LAI; α is the woody-to-total area ratio; γ_E is the needle-to-shoot area ratio; and Ω_E is the element-clumping index describing the effect of clumping at a scale larger than the shoots (Stenberg *et al.* 1994, Chen and Cihlar 1995, Stenberg 1996a, Chen *et al.* 1997, Kucharik *et al.* 1998, Gower *et al.* 1999, Eriksson *et al.* 2005).

Effective LAI, or L_e, was measured using a LAI-2000 plant canopy analyser (PCA) (LI-COR Inc., Cambridge, UK) between 20 and 30 June 2005. Measurements were made either at dusk or at dawn to ensure diffuse radiation from all directions of the atmosphere. For the above canopy readings, one sensor was placed either in a tower rising above the canopy or in a large open field. In the open fields, the sensor was placed at a distance of at least 3.5 times the height of the closest trees. The within-stand measurements were made by walking three evenly distributed transects through the sites, measuring transmitted radiance every 1.5 m. The number of measurements was between 45 and 60, depending on the size of the site. The field of view of the sensor within the stand had the same compass azimuth angle as the sensor in the field. View restrictors of 270° were used to restrict the incoming radiation and to prevent the operator from being viewed. A software programme, C2000 (LI-COR Inc., Cambridge, UK), coordinated the above- and below- canopy readings, with no time difference larger than 7.5 s.

For homogenous deciduous sites, woody-to-total area ratio (α) was estimated using LAI-2000 measurements made between 11 and 22 April 2005, when leaves were absent, by dividing it by the LAI-2000 measurement made in June. One average woody-to-total area ratio was calculated for birch and one for the other deciduous trees (table 1). In these calculations, values from both Forsmark and Laxemar were used, as there were too few deciduous sites in Forsmark. Coniferous forests are evergreen in these areas and the woody-to-total area ratio could not easily be estimated. Therefore, literature values were used instead. The pine value was taken from Smolander and Stenberg (1996). For spruce, no value was found for *Picea abies* and an average value for *Picea mariana* and *Picea sitchensis* was used instead (Gower *et al.* 1999). Woody-to-total area ratios for pine, spruce, birch and the other deciduous trees were used to calculate average ratios for the mixed and coniferous forest sites.

The needle-to-shoot area ratios, γ_E, were estimated using literature values of the shoot silhouette area to total needle area, *S*, (Stenberg 1996b) and:

$$\gamma_E = 1/(4\,S), \tag{2}$$

where the factor 4 was necessary as needles are convex and the LAI was defined as half the total leaf area (Stenberg 1996a). For deciduous trees, γ_E was set to 1 (table 1). To obtain the needle-to-shoot area ratio of the sites, the proportions of each species multiplied by their respective needle-to-shoot area ratio were calculated and added together.

The element-clumping index (Ω_E) was estimated using a tracing radiation and architecture of canopies (TRAC) instrument (Leblanc *et al.* 2002). All measurements were made in bright sunlight between 20 and 30 June 2005. At each site, measurements were made along five evenly distributed 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 site, and split into 5 m sections.

To calculate the clumping index, the TRACWin software was used. In the calculations, woody-to-total area ratio, needle-to-shoot area ratio and mean element width, *W*, were needed. To estimate *W*, the lengths and diameters of 10 shoots of pine, 10 shoots of spruce, 10 leaves of birch and 10 leaves of oak were measured. *W* was calculated by:

$$W = (G \times A)^{0.5}, \tag{3}$$

where *G* is the canopy extinction coefficient, which can be approximated to 0.5 in natural canopies (Leblanc *et al.* 2002) and *A* is the area of the element. We approximated that leaves are circular and shoots are cylinders in the area calculation of the

Table 1. Values of woody-to-total area ratio (α), needle-to-shoot area ratio (γ_E) and mean element width (W) used for estimation of LAI.

Species	α	γ_E	W (mm)
Pine	0.14	1.70	71.4
Spruce	0.17	1.33	47.1
Birch	0.49	1.00	30.7
Deciduous	0.25	1.00	43.8

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elements. Mean element width, W, is given in table 1. Finally, the LAI was calculated using equation (1).

2.3 *Relationship between LAI and NDVI*

For the Laxemar investigation area, a map showing the NDVI produced by Boresjö Bronge (2004) was used. Boresjö Bronge (2004) calculated the NDVI by taking:

$$\mathrm{NDVI} = (\rho_{\mathrm{NIR}} - \rho_{\mathrm{red}})/(\rho_{\mathrm{NIR}} + \rho_{\mathrm{red}}), \tag{4}$$

where ρ_{NIR} is the near-infrared band and ρ_{red} is the red band. X13 was used as ρ_{NIR} and X12 as ρ_{red} from images taken by the high resolution visible infrared (HRVIR) detector on 11 July 1999 aboard SPOT-4. The digital numbers were not calibrated into reflectance or radiance or corrected for atmospheric effects as no calibration information for the SPOT-4 image could be found (Boresjö Bronge 2004). For Forsmark, an NDVI image was produced based on equation (4) and Landsat 5 TM4 as ρ_{NIR} and TM3 as ρ_{red} from 3 June 2000 (path/row: 193/018). The satellite data were not radiometrically calibrated, as the Laxemar image was not, and since only relative analysis within the image was going to be carried out. However, uncalibrated NDVI images cannot be directly compared with the NDVI images from other studies.

The NDVI fraction gives values between –1 and 1, and it was converted into positive values ranging between 0 and 254 for both the SPOT and the Landsat data from:

$$\mathrm{NDVI}_{254} = 127((\mathrm{NDVI}) + 1). \tag{5}$$

The Forsmark NDVI image was corrected geometrically to the Swedish coordinate system Rikets nät (RT 90). A total of 25 control points were collected from a cadastral map. Control points were, for example, road crossings, buildings, canals and islands. A first-degree polynomial transformation was used to describe the relationship between the two coordinate systems. The root mean square error was 8.7 m. To interpolate the values from the uncorrected image to the corrected image, a cubic convolution resampling was carried out.

The NDVI values were extracted for the investigated sites in both Laxemar and Forsmark. The pixels of the NDVI images (400 and 900 m^2 for SPOT and Landsat, respectively) were of approximately the same size as the measured sites and therefore no merging of pixels was carried out.

Both the SKB sites and the National Forest Inventory (NFI) sites in Laxemar and Forsmark were separated into four groups: all sites, homogenous coniferous sites, homogenous deciduous sites and mixed sites. To test whether there were any relationships between field-estimated LAI and NDVI and between field-estimated effective LAI and NDVI, curve estimations were carried out. Tests were done for both Laxemar and Forsmark. No regressions were carried out for deciduous sites in Forsmark, as we did not have enough data. Seven different curve-estimation models were used: linear ($L = kN + b$), logarithmic ($L = b + k \ln(N)$), power ($L = bN^k$), compound ($L = k_1 k_2^{\,N}$), s-curve ($L = \exp(b + k/N)$), growth ($L = \exp(b + kN)$) and exponential ($L = b \exp(kN)$), where k are the regression coefficients, b are the regression constants, L is LAI or effective LAI and N is NDVI. Residuals were checked for normal distribution using a Kolmogorov–Smirnov test. SPSS 12.0.1 for Windows was used for all statistical

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analysis, and the regressions were labelled significant if the *p*-value was lower than 0.05, a trend if they were between 0.05 and 0.1 and insignificant if higher than 0.1.

2.4 *Evaluation of MODIS LAI product*

The NDVI images were stratified to different vegetation types using vegetation maps from Boresjö Bronge and Wester (2003). For Forsmark, a Swedish terrain type classification (Lantmäteriet 1999) was also used. For Forsmark, additional land surrounding the investigation area was included in the analysis to increase the number of data. Layers of coniferous forest, deciduous forest, mixed forest and open and water areas were created. The NDVI pixels were copied into the different layers.

For Laxemar, the strongest regressions from the curve estimations with field-estimated LAI against NDVI for homogenous coniferous sites, homogenous deciduous sites and mixed sites were applied to their respective NDVI dataset. The different layers were aggregated and an NDVI-based LAI image of Laxemar was created.

For Forsmark, there were no significant relationships between field-estimated LAI and NDVI when the sites were separated into the different classes, but when all sites were included in the regressions there was an exponential trend relationship between field-estimated effective LAI and NDVI. Field-estimated effective LAI was extrapolated using the exponential regression against the NDVI on the coniferous, deciduous and mixed forest layers. To estimate the LAI, average woody-to-total area ratios, average needle-to-shoot area ratios and average element-clumping indices were calculated for the deciduous, coniferous and mixed sites (table 2). These values were used in equation (1), with each vegetation type layer of effective LAI to create an NDVI-based LAI image for Forsmark.

For both investigation areas, MODIS LAI coverage (collection 4) was extracted from band 2 of MOD15A2. To ensure the quality of the pixels, quality control (QC) bits from MODLAND was used. Data with QC bits with values 0 and 1 were used, whereas those with values of 2 and 3 were removed from the analysis. Good-quality pixels from the MODIS LAI product of 26 June to 3 July 2005 were used. For the pixels with poor quality, data was taken from 4 to 12 July 2005. In Forsmark, there were still a few poor-quality pixels left and, for these, data from 13 to 21 July 2005 were taken.

The MODIS data were geometrically corrected to the Swedish coordinate system, Rikets nät RT 90 using the same method as above for the Forsmark NDVI image. Control points were collected from the NDVI images and sea and lake coastlines from a map of Sweden. A total of 25 control points were collected spread out over the investigation areas. The root mean square error was calculated to 230 m for Forsmark and 231 m for Laxemar, i.e. slightly less than 1/4 of a pixel. The resampling method used was the nearest neighbour method to ensure that low-quality pixels would not disturb the high-quality pixels.

Table 2. Woody-to-total area ratio (α), needle-to-shoot area ratio (γ_E) and element-clumping indices (Ω_E) used in equation (1) to correct effective LAI for Forsmark.

Vegetation types	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

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The MODIS LAI product was compared to NDVI-based LAI by recalculating NDVI-based LAI to a 1 km resolution by averaging the NDVI-based LAI values within each MODIS pixel. In the calculations, the LAI for water and open areas were given a value of 0. A linear regression between NDVI-based LAI and MODIS LAI was performed for both Forsmark and Laxemar, and residuals were checked for normal distribution using a Kolmogorov–Smirnov test. Since data was not normally distributed, Spearman rank correlations between NDVI-based LAI and the MODIS LAI product were carried out for both investigation areas.

3. Results

3.1 *Relationship between LAI and NDVI*

In Laxemar, there were no significant relationships for field-estimated LAI of all sites against the NDVI, while several significant curve-estimation models predicting field-estimated effective LAI were observed. A logarithmic regression gave the best explanation (p-value = 0.000, R^2 = 0.325). When the coniferous, deciduous and mixed forest sites were separated, clear relationships between field-estimated LAI and NDVI were shown. This indicates that there was a large difference between coniferous and deciduous sites in their relationships between field-estimated LAI and NDVI. For coniferous sites, the best-fit curves were exponential, compound and growth functions, (p-value = 0.000, R^2 = 0.518); for deciduous sites it was the s-curve (p-value = 0.004, R^2 = 0.769); and for mixed sites there was

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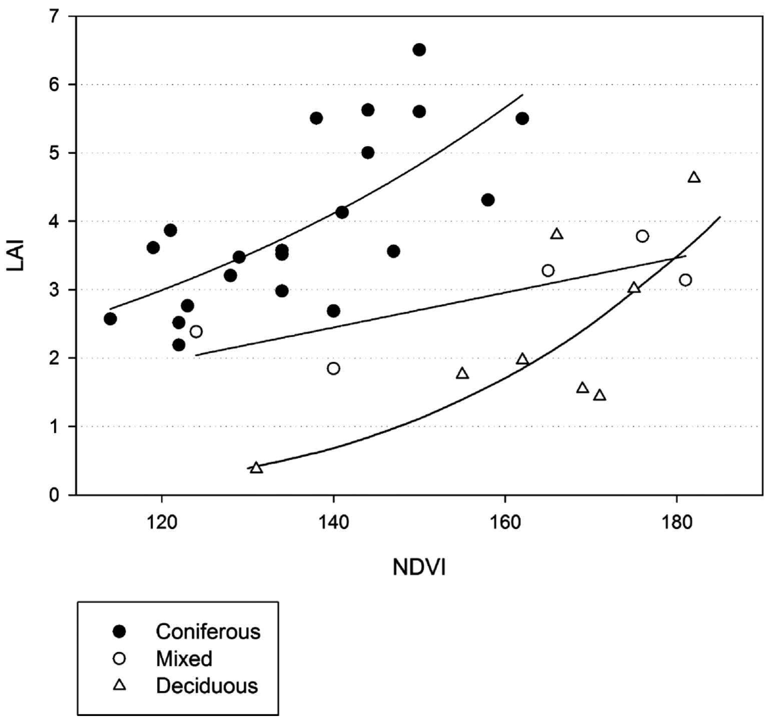

Figure 1. LAI against NDVI for the different vegetation types in Laxemar. The equations were $L = b\exp(k\,N)$ for coniferous sites, $L = \exp(b + k/N)$ for deciduous sites and $L = k\,N + b$ for mixed sites. In the equations, k and b are regression coefficients, L is LAI and N is NDVI.

Table 3. Equations used for producing LAI images of the Laxemar and Forsmark investigation areas. Equations follow the form $L = b\ \exp(kN)$ for coniferous sites in Laxemar, $L = \exp(b + k/N)$ for deciduous sites in Laxemar and $L = kN + b$ for mixed sites in Laxemar. For all sites in Forsmark, the equation was $L_e = b\ \exp(kN)$. In the equations L is LAI, N is NDVI and L_e is effective LAI. These equations can only be used against the NDVI datasets of SPOT, 11 July 1999 for Laxemar and Landsat 5, 3 June 2000 for Forsmark, since images were analysed without calibration.

Vegetation types	Investigation area	Degrees of freedom	b	k	F-value	p-value	R^2
Coniferous	Laxemar	20	0.383	0.017	20.40	0.000	0.52
Deciduous	Laxemar	7	6.942	–1025.023	19.94	0.004	0.77
Mixed	Laxemar	4	–1.115	0.025	5.73	0.097	0.66
All	Forsmark	17	0.960	0.006	3.44	0.082	0.18

a linear-trend relationship (p-value = 0.097, R^2 = 0.656) (figure 1, table 3). There were also significant relationships to field-estimated effective LAI, and these were stronger than the relationship to field-estimated LAI for coniferous (linear regression, p-value = 0.000, R^2 = 0.586) and mixed (linear regression, p-value = 0.063, R^2 = 0.736) sites while they were lower for deciduous sites (exponential regression, p-value = 0.011, R^2 = 0.684).

In Forsmark, no relationship could be found between field-estimated LAI and NDVI, not even for the separated coniferous and mixed forest sites. For all sites, trend relationships could, however, be seen with field-estimated effective LAI against the NDVI. The strongest regressions were compound, exponential and growth functions, all with the same statistical significance (p-value = 0.082, R^2 = 0.177) (table 3).

3.2 *Evaluation of MODIS LAI product*

The values of the MODIS LAI product were both higher and showed larger variances than NDVI-based LAI (figure 2). Average MODIS LAI in Laxemar was 5.07 ± 1.24 and in Forsmark, it was 5.34 ± 1.34. For the same pixels, average NDVI-based LAI was 3.00 ± 0.82 for Laxemar and 2.87 ± 0.33 for Forsmark. The Spearman rank correlation between MODIS LAI and NDVI-based LAI was 0.028, but not significant (sample size 2717, p-value = 0.148), in Forsmark. In Laxemar, it was 0.392 and significant (sample size 239, p-value = 0.000).

4. Discussion

4.1 *Field-estimated LAI*

Previous comparative studies have shown that the gap-fraction method is reliable for field sampling of the LAI (Chen 1996, Chen *et al.* 1997, Gower *et al.* 1999, Eriksson *et al.* 2005). An error analysis performed by Chen (1996) indicated that the LAI measured with optical instruments has an accuracy of between 15 and 40%. Approximately 3–5% of the error originates 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 with regards to direct destructive methods; the error analysis performed by Chen (1996) indicated that, in coniferous stands, optically based methods could, if performed correctly, give even more accurate results than direct destructive methods.

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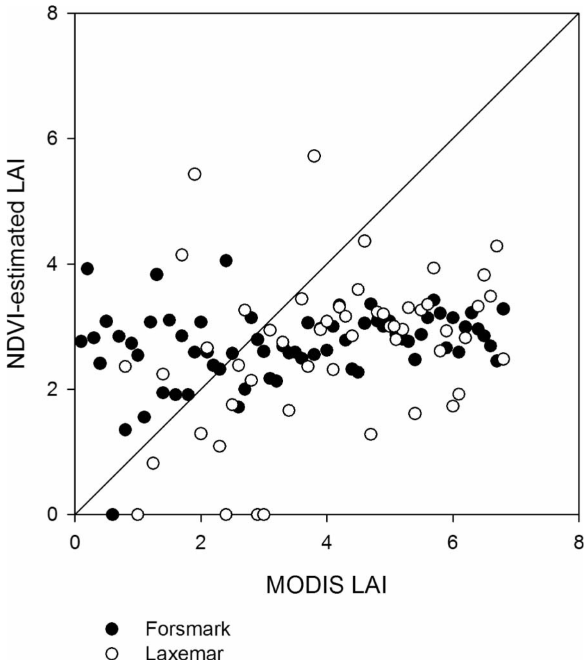

Figure 2. MODIS LAI against NDVI-based LAI for Laxemar and Forsmark. The line is the one to one theoretical relationship.

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Correction factors used for correcting effective LAI are not universal and should be measured in each of the sites where the LAI was to be corrected (Stenberg 1996a). In this study, it was not possible to estimate needle-to-shoot area ratio and woody-to-total area ratio for each site due to limited resources and due to the destructive nature of the estimation techniques. It should be mentioned that these correction factors could vary due to, for example, environmental conditions, fertilization, competition for sunlight and latitude (Stenberg *et al.* 1995, Stenberg 1996b). This may have affected the field-estimated LAI values, but according to Chen *et al.* (1997), there is not much variation in the correction factors once the stands have become mature, which justifies the use of average values.

Another known potential error of the gap-fraction method is saturation of gap-fractions at high LAI, which would result in underestimation of the LAI (Leblanc and Chen 2001, Albaugh *et al.* 2004). However, in this study, field-estimated LAI was below 6 throughout the areas, and therefore saturation of the gap fractions should not be a problem (Leblanc and Chen 2001).

Alternative methods for the correction of effective LAI have been suggested, but none has been truly successful. Nilson *et al.* (1999) used stand characteristics in gap-fraction formulas to estimate the LAI, but these estimations are not easy to carry out, as they require information about the canopy structure. New theories have been under development since the introduction of high-resolution hemispherical digital cameras that make sampling easier, less destructive and more accurate (Weiss *et al.* 2004). In the future, they may result in more precise estimations of the LAI.

4.2 *Relationship between LAI and NDVI*

Previous studies have shown that the relationships between the NDVI and LAI are site specific and differ depending on vegetation type (Myneni *et al.* 1997b, 2002, Nilson *et al.* 1999, Turner *et al.* 1999, Eklundh *et al.* 2001, 2003, Stenberg *et al.* 2004). In this study, several curve-estimation models were tested and the regressions that best explained field-estimated LAI were of a weakly exponential character for coniferous and deciduous sites. This shows that the NDVI was saturated at higher LAI values for these ecosystems. The mixed sites showed a linear relationship caused by differences in canopy structure, the NDVI was lower for coniferous forests than for deciduous forests, while field-estimated LAI was slightly higher for coniferous forests than for deciduous forests. The mixed sites end up somewhere in between and hence have a linear relationship (figure 1).

Correlations between the NDVI and LAI were relatively weak and the main problem with the investigation was the small sample size. In Forsmark, deciduous sites could not be investigated, and there was no correlation between field-estimated LAI and NDVI for the coniferous and mixed sites. However, measurements of effective LAI do not differ between coniferous and deciduous stands, they are simply based on the radiation transmission through the canopy (Chen *et al.* 1997). Therefore, effective LAI for all stands could be used and it was correlated to the NDVI, while corrected LAI was not. Additionally, the few existing data points were needed in the analysis, and this prevented the separation of some data to be used in an evaluation. Another potential error was that the NDVI image pixels were the same size as the measured sites. There were potential positional errors caused by cubic convolution resampling, geometrical correction and that the NDVI image pixels and the field-measured sites do not always line up. Another negative effect could be that reflectance from neighbouring pixels affected the spectral response of the pixel used in the study. It would have been better if the measured sites had been bigger so that average values of several pixels could have been used. It is concluded though that the sites are situated within larger homogenous stands and that these positional and spectral errors should not disturb the analysis too much.

Still, the LAI was correlated to the NDVI and the investigation shows that the NDVI can be used for spatial and temporal extrapolation of the LAI. Extrapolating LAI spatially and temporally is a strong tool in the study of global carbon budgets and its relation to physiological processes and ecosystem features could be used for up-scaling these.

4.3 *Evaluation of MODIS LAI product*

The MODIS team has defined the accuracy of their product to 0.5 LAI (Wang *et al.* 2004), but, on average, the MODIS overestimated the LAI by 2.07 in Laxemar and 2.48 in Forsmark. Overestimations of LAI by the MODIS have also been seen in earlier studies (Cohen *et al.* 2003, Wang *et al.* 2004). A problem could be biome misclassification due to spatially complex sites, and Cohen *et al.* (2003) showed that out of four different vegetation types, the boreal forests were least correctly classified by the MODIS. Another problem is the issues of the scale caused by different pixel sizes in the MODIS and NDVI images. The spatial complexity of the investigation areas was captured in the NDVI images of Landsat and SPOT, whereas it was missed in the coarse pixels of the MODIS (Myneni *et al.* 2002, Cohen *et al.* 2003, Verbyla

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2005). In the NDVI-based LAI image, open areas were given LAI values of 0, lowering the LAI compared with the MODIS, which assumed forests over the entire pixel.

The MODIS LAI had a larger scatter than the NDVI-based LAI, as seen in figure 2, and the reason for this could be that the MODIS algorithm needs improvement due to influences from the understorey vegetation (Wang *et al.* 2004). It could be that the understorey and the mixture of vegetation have affected differently in diverse parts of the image, increasing the variation in comparison to the NDVI-based LAI image (Myneni *et al.* 2002, Wang *et al.* 2004, Verbyla 2005). Other explanations could be that atmospheric disturbances could have a different effect in different parts of the image (Wang *et al.* 2004).

Validation of the MODIS LAI product requires an integrated approach using field measurements, empirical modelling and remote sensing. Small regional area (but still large enough to get data for a validation) field samples, covering the variability of the investigation areas, and fine-grained satellite data have been used to investigate the applicability of the MODIS LAI product. Errors in the comparison could originate from the resampling of the MODIS data. The resampling method used was the nearest neighbour method, instead of cubic convolution, which should have given the best approximation. However, with the cubic convolution method, values are averaged and surrounding pixels affect the data point. In the MODIS LAI images, there were low-quality pixels; these would affect the product and we therefore choose the nearest neighbour method as the least disturbing resampling method. Furthermore, the MODIS images were from the end of June 2005, when field measurements were made, and the Landsat and SPOT developed images were from 2000 and 1999, respectively. If this were a problem, however, the MODIS LAI would have been lower than NDVI-based LAI, as trees had been removed between these time periods.

The main improvement that could be done to the MODIS LAI product would be to reduce the scale issues by increasing the spatial resolution. This would give spatial complexity and increase the accuracy and biome classification of the product. Cohen *et al.* (2003) have suggested another improvement. The LAI algorithm is strongly dependent on the red and near-infrared bands, and they showed that the LAI is also strongly correlated to the short-wave infrared MODIS bands (5, 6 and 7). Increasing the influence of these additional MODIS bands in the algorithm would make the MODIS LAI product better (Cohen *et al.* 2003).

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4.4 *Conclusions*

This study set out to investigate the relationship between the LAI and NDVI. The technique estimating the LAI with gap-fraction methods and correlating field-estimates to satellite data is commonly used and the main potential errors are well known. The main problems are, for example, uncertain correlation coefficients, positional errors caused by resampling and geometrical corrections and influence from neighbouring pixels. These errors are shown by the weak relationships between the LAI and NDVI. However, the LAI were still significantly correlated to the NDVI, and the NDVI is therefore a strong tool for spatial and temporal extrapolation of LAI data in the study of global carbon budgets.

We also wanted to compare the NDVI-based LAI with the LAI product from the MODIS, to see if the MODIS product could be used for continuous estimates of the LAI in small boreal regions. The comparison indicated that the MODIS LAI was correlated to the LAI in Laxemar but not in Forsmark. However, the MODIS LAI overestimated the LAI and the variation was greater than the NDVI-based LAI. The main explanation was probably scale issues, caused by the heterogeneous landscape of the investigation areas resulting in biome misclassifications, and open areas lowering the NDVI-based LAI estimates in comparison to the coarse pixels of the MODIS. Therefore, our conclusion was that the MODIS product should not be used for future estimates of the LAI for small boreal regions such as the Laxemar and the Forsmark investigation areas.

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