Reduced Simple Ratio Better than NDVI for Estimating LAI in Finnish Pine and Spruce Stands

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Estimation of leaf area index (LAI) using spectral vegetation indices (SVIs) was studied based on data from 683 plots on two Scots pine and Norway spruce dominated sites in Finland. The SVIs studied included the normalised difference vegetation index (NDVI), the simple ratio (SR), and the reduced simple ratio (RSR), and were calculated from Landsat ETM images of the two sites. Regular grids of size 1 km^2 with gridpoints placed at 50 m intervals were established at the sites and measurements of LAI using the LAI-2000 instrument were taken at the gridpoints. SVI-LAI relationships were examined at plot scale, where the plots were defined as circular areas of radius 70 m around each gridpoint. Plotwise mean LAI was computed as a weighted average of LAI readings taken around the gridpoints belonging to the plot. Mean LAI for the plots ranged from 0.36 to 3.72 (hemisurface area). All of the studied SVIs showed fair positive correlation with LAI but RSR responded more dynamically to LAI than did SR or NDVI. Especially NDVI showed poor sensitivity to changes in LAI. RSR explained 63% of the variation in LAI when all plots were included (n = 683) and the coefficient of determination rose to 75% when data was restricted to homogeneous plots (n = 381). Maps of estimated LAI using RSR showed good agreement with maps of measured LAI for the two sites.

Keywords Leaf Area Index, Landsat ETM, spectral vegetation indices, boreal coniferous forests

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1 Introduction

1.1 Background

The leaf area index (LAI) is an important characteristic of forest stands because of the role of green leaves in controlling many biological and physical processes driving the exchange of matter and energy flow (Cannell 1989). In particular, because LAI correlates strongly with the fraction of absorbed photosynthetically active radiation (fAPAR) – the energy available for net primary production (NPP), it constitutes a key parameter for forest growth (Monteith 1977, Jarvis and Leverenz 1983). Furthermore, since the leaf area responds rapidly to different stress factors and (changes in) climatic conditions, LAI could serve as a useful indicator to characterize the condition of the forest ecosystem in the research of global change (Myneni et al. 1997a).

Remote sensing provides the only feasible alternative for the estimation or monitoring of LAI at regional scales. Models developed for application to remotely sensed optical data rely on physically based relationships between LAI and canopy spectral reflectances, typically expressed in the form of spectral vegetation indices (SVIs). SVIs used for the estimation of canopy parameters attempt to enhance the spectral contribution of vegetation while minimising those from the background (Huete 1989, Verstraete and Pinty 1996). A leaf-specific spectral characteristic not present in (bare) soil spectra is the sharp increase in scattering at around 700 nm, called the “red edge” (e.g. Lillesand and Kiefer 1994). For estimation of green vegetation (LAI), thus, SVIs using the ratio of some combination of red and near-infrared (NIR) reflectance, such as the normalised difference vegetation index (NDVI) or the simple ratio (SR), are commonly used (Asrar 1989, Myneni et al. 1997a).

Fairly strong but site specific relationships between (effective) LAI and NDVI (or SR) have been found in various studies across different vegetation types (e.g. Curran et al. 1990, Spanner et al. 1990, Nemani et al. 1993, Law and Waring 1994, Jakubauskas and Price 1997, White et al. 1997, Chen et al. 1999, Nilson et al. 1999, Turner et al. 1999, Eklundh et al. 2001). (The term ‘effective LAI’ refers to that ground estimates of LAI are commonly obtained using optical instruments which tend to underestimate the true LAI in (coniferous) canopies with a clumped distribution of foliage (Stenberg et al. 1994, Chen 1996, Stenberg 1996)). The use of NDVI for LAI estimation on regional scales thus would require stratification into vegetation types (land cover classes) with different, class specific NDVI-LAI relationships. For example, Myneni et al. (1997b) classified global land cover into six different canopy structural types (“biomes”) with specified (model derived) NDVI-LAI relationships, which then were applied to estimate global LAI. The basic condition for the outcome (estimation accuracy) of methods where stratification is used for NDVI (SVI) based estimation of LAI over larger geographical scales (across vegetation types) is that within the different classes (“strata”) sufficiently invariant relationships between LAI and the considered SVI exist. In addition, the variable used for the estimation (the measured SVI) should be sensitive to changes in the target variable (LAI) throughout its natural range. A well documented problem with SVIs such as the NDVI is that they tend to saturate at high levels of LAI (e.g. Sellers 1985).

1.2 Aim of Study

Studies from the boreal forest zone indicate that NDVI is not dynamic enough to be suitable for the estimation of LAI (Chen and Cihlar 1996, Häme et al. 1997, Nilson et al. 1999, Eklundh et al. 2001, Rautiainen et al. 2003). The range of NDVI of boreal coniferous forests is typically narrow, and the index reaches nearly saturated values already at moderate values of LAI. This can be explained by the presence of green understorey, causing a non-contrasting background reflectance in the visible part of the spectra (Nilson and Peterson 1994, Myneni et al. 1997b, Nilson and Kuusk 2002). It has long been recognised that inclusion of a middle infrared (MIR) spectral band in SVIs based on visible and NIR reflectance can provide useful complementary information on the geometrical structure of the canopy and on the optical properties of the underlying soil (Baret et al. 1988, Nemani et al. 1993). To adjust for differences in canopy closure and background reflectance in the retrieval of LAI of boreal forests, Brown et al. (2000) introduced a MIR corrected modification to the simple ratio which was termed the reduced simple ratio (RSR). The modification was found to reduce the effect of background reflectance and increase the sensitivity to changes in LAI. Results from Brown et al. (2000) and from a later study by Chen et al. (2002), comprising data from the major boreal tree species in Canada, showed that for both coniferous and deciduous stands RSR correlated better with LAI than did SR.

The suitability of RSR for the estimation of LAI in coniferous stands is supported by results of Eklundh et al. (2003) where the performance of a number of vegetation indices on coniferous and deciduous forests in southern Sweden was compared. In the study RSR did not perform well for the deciduous stands (r = 0.10) but the correlation increased considerably when moving to coniferous stands (r = 0.75). Correction for needle clumping in the coniferous stands was done by multiplying the LAI-2000 estimate by a species specific value of the ratio of needle to shoot silhouette area using data for pine and spruce from Stenberg (1996). In analysing the relationships between LAI and different SVIs, Eklundh et al. (2003) in addition used two other corrections to the LAI-2000 estimate which were built to account for grouping at scales larger than the shoot (Chen 1996, Kucharik et al. 1998). However, these corrections resulted in clearly poorer relationships (correlation) between LAI and the SVIs, indicating that the optical estimate provided directly by the LAI-2000 corresponds better to the LAI "seen" by the satellite. Thus, the corrections for grouping are perhaps best done a posteriori to the SVI based retrieval of LAI.

In this study, the suitability of NDVI, SR and RSR for the estimation of LAI was investigated based on a large data set comprising 683 plots in two Finnish forest sites dominated by Scots pine (*Pinus sylvestris* L.) and Norway spruce *(Picea abies* (L.) Karst.). LAI of the plots was measured using the LAI-2000 plant canopy analyzer, and the reflectance data was from two Landsat ETM images of the sites. Selected parts of the data from the two sites have been used in previous investigations dealing with the retrieval of LAI using the Kuusk and Nilson (2000) forest reflectance model (Rautiainen 2002, Rautiainen et al. 2003). The Scots pine dominated stand has also been used for validation of the MODIS LAI product developed by Knyazikhin et al. (1998) (Tian et al. 2003, Wang et al. 2003).

2 Material and Methods

2.1 Site Description

The study sites were located in Puumala (61°31.6'N, 28°42.4'E) in south-eastern Finland and in Suonenjoki (62°40.9'N, 27°28.7'E) in central Finland. Stand measurements were made in July 2000 (Puumala) and July 2001 (Suonenjoki). The Puumala site was located in a managed forest dominated by Scots pine (*Pinus sylvestris* L.) with Norway spruce (*Picea abies* (L.) Karst.) as the subdominant species. Understorey vegetation was composed mainly of dwarf shrubs (*Vaccinium myrtillus* L. and *Vaccinium vitis-idaea* L.). A 1 km × 1 km grid with 400 regularly spaced gridpoints was established at the site. The Suonenjoki site was dominated by Norway spruce with Scots pine as the subdominant species. Understorey vegetation was more abundant and was composed mainly of *Vaccinium myrtillus* and a few grasses. At the Suonenjoki site, a 0.65 km × 1.4 km grid with 370 gridpoints was established. In both stands, the gridpoints representing the plot centres were marked by sticks located at 50 m intervals on parallel transects 50 m apart from each other (Fig. 1). The geographic coordinates of the centre points of the plots were measured with GPS (Trimble Pro XR).

Stand data of the plots were represented by mean values obtained from carrying out relascope sampling at the centre of each plot. Tree species composition, stand density, basal area, height, crown length and breast height diameter of trees, and site type were recorded.

2.2 LAI Measurements

Measurements of leaf area index were made using the LAI-2000 Plant Canopy Analyzer (Li-Cor Inc., Nebraska, USA). The measuring proce-

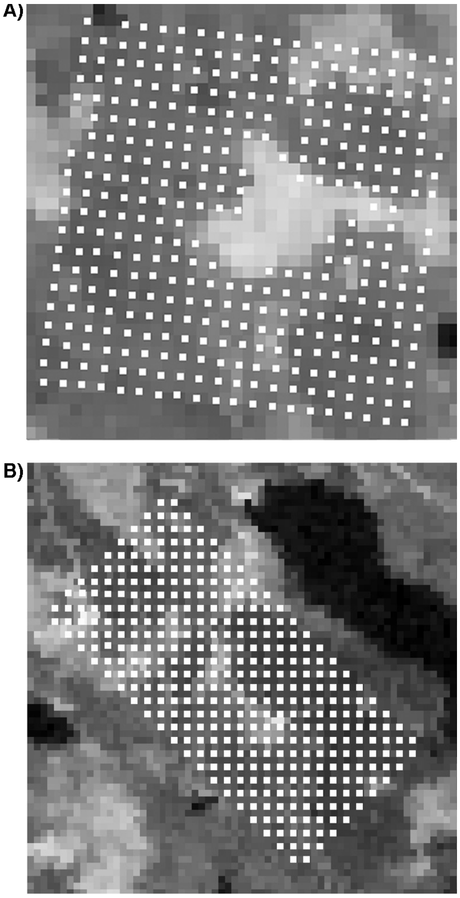

Fig. 1. Grid design on top of Landsat ETM RGB-composition of channels 5, 4, and 3. a) Puumala site. b) Suonenjoki site.

dure was similar at both sites. Two LAI-2000 units were used to obtain simultaneous readings below and above the canopy. "Above-canopy" readings were collected automatically at regular intervals (every 15 or 30 s) in open fields within the sites. The extensive LAI measurements (over the 1 km^2 grids) required a prolonged period of time (several weeks) during which the illumination conditions were not always optimal for the LAI-2000 instrument (i.e. evenly overcast sky). Thus, to prevent direct sunlight from reaching the sensors a view cap occluding 90º of the sensor's azimuthal field of view (FOV) was used, which at same time occluded the operator from the FOV. During measurements the sensors were oriented so that the FOV was always the same for the above- and below-canopy readings. Below-canopy measuring height was 1 m above the ground, so that only trees were included in the FOV. Readings with the LAI-2000 were taken at the plot centre point, and at 6 m distance from the centre point in each of the four cardinal directions (north, south, east and west). Three readings were taken at each point, and the plot centre value of LAI was computed as the average over the 15 (3 × 5) measurements.

2.3 Satellite Data

Two Landsat 7 ETM images from Puumala and Suonenjoki were used in the analyses (Table 1). The rectified image of Puumala was provided by the University of Boston as part of the MODIS LAI co-operation at the site (Tian et al. 2003). The Suonenjoki image was rectified by VTT (Technical Research Centre of Finland) using linear nearest neighbor sampling based on ground control points. The average RMSE of the control points was about 0.5 pixels (i.e. about 15 m). Radiometric calibration and atmospheric correction of the images were done by VTT Technical Research Centre of Finland and the original pixel size (30 m × 30 m) was maintained. The radiometric processing transformed the digital numbers to TOA (Top of Atmosphere) reflectance using calibration coefficients from the Landsat ETM header files and the solar irradiance corrected for the day of acquisition (Andersson 2000). The atmospheric corrections were carried out using the SMAC (Simplified Method for Atmospheric Corrections) algorithm of Rahman and Dedieu (1994), which enables pixelwise corrections. For the atmospheric optical thickness, a constant value of 0.1 at 550 nm was applied in the correction.

2.4 Spatially Averaged Estimates of LAI and the Spectral Reflectances

The SVI-LAI relationships were examined at a spatial scale represented by circular areas of radius 70 m around the gridpoints. The spectral reflectances of the (30 m × 30 m) Landsat ETM pixels whose midpoints fell within 70 m from a

Table 1. The Landsat 7 ETM satellite images used in the study.

Site	Date	Sun elevation angle	Sun azimuth angle	Pixel size
Puumala	June 10, 2000	50.5°	160.3°	30 m × 30 m
Suonenjoki	July 6, 2001	48.6°	159.5°	30 m × 30 m

Table 2. Ranges of stand variables and LAI for the plots.

	Suonenjoki	Puumala
Stand volume, m^3/ha	6–631	3–362
LAI_{mean}	0.74–3.72	0.36–3.38
Mean height, m	5–22	3–20
Mean breast height diameter, cm	4–34	3–27
Basal area, m^2/ha	2–69	1–46
Stand density, stems/ha	22–7898	12–4615

gridpoint were thus averaged to give the plotwise value. The corresponding LAI value (LAI_{mean}) was calculated as a weighted mean, where 60% weight was given to LAI measured around the centre gridpoint, and 10% weight each to LAI of the four nearest gridpoints.

Plot size was chosen to be comparable with the area measured by the LAI-2000 at the plot centres (gridpoints), although the area represented by the instrument reading cannot be precisely defined. The total area "seen" by the LAI-2000 instrument can be calculated as ca. 3.5 times the maximum tree height and, so, the chosen plot size would correspond to the LAI-2000's field of view for a dominant tree height of ca 20 m. However, the detector rings of the LAI-2000's optical sensor all see different parts of the canopy, and trees closer to the sensor contribute more to the LAI value than trees situated further away. Thus, changes in LAI towards the border of the FOV would not have an appreciable effect the estimate of LAI obtained at the plot centre. To reduce such "border effects", LAI_{mean} was calculated with some weight given to LAI measured around the four neighbouring gridpoints (situated close to the border of the FOV).

2.5 Spectral Vegetation Indices

Three different SVIs were tested for their sensitivity to (changes in) LAI: the normalised difference vegetation index (NDVI), the simple ratio (SR), and the reduced simple ratio (RSR). They were calculated from the atmospherically corrected reflectance (r) values of Landsat ETM spectral channels 3 (red; 630–690 nm), 4 (NIR; 750–900 nm), and 5 (MIR; 1550–1750 nm) as:

$$SR = \frac{\rho_{ETM4}}{\rho_{ETM3}} \tag{1}$$

$$NDVI = \frac{\rho_{ETM4} - \rho_{ETM3}}{\rho_{ETM4} + \rho_{ETM3}} \tag{2}$$

and

$$RSR = \frac{\rho_{ETM4}}{\rho_{ETM3}} * \frac{\rho_{ETM5\max} - \rho_{ETM5}}{\rho_{ETM5\max} - \rho_{ETM5\min}} \tag{3}$$

where $\rho_{ETM5max}$ and $\rho_{ETM5max}$ (Eq. 3) were represented by the largest and smallest reflectance values in channel 5 for the Landsat ETM pixels covering the 1 km^2 grid areas. The area contained forest and open areas, but no surface water.

3 Results

Plotwise mean LAI (LAI_{mean}) ranged from 0.36 to 3.38 in Puumala and from 0.74 to 3.72 in Suonenjoki (Table 2). The LAI_{mean} distribution of the Puumala plots was close to normal distribution and was centred around 1.5 to 2, whereas in Suonenjoki LAI values were on average larger and had no clear peak value but were fairly uniformly distributed between 1.0 and 3.5 (Fig. 2).

The reflectance in Landsat ETM spectral channels 3 (red), channel 4 (NIR), and 5 (MIR) all showed a decreasing trend with increasing LAI (Fig. 3). In NIR the dependency with LAI was, however, weak and in contrast to the other channels which had similar ranges at both sites, NIR reflectance appeared somewhat higher at the

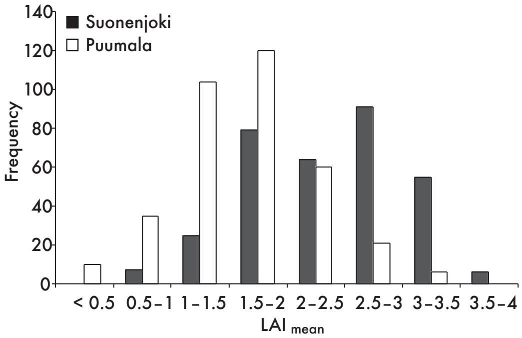

Fig. 2. Frequency distributions of LAI at Puumala and Suonenjoki.

Suonenjoki site than at the Puumala site. Several plots from the Puumala site with LAI$_{\mathrm{mean}}$ under 1.0 could be distinguished as a separate group in all the three studied ETM bands due to their considerably low reflectance (Fig. 3). This results from the centre points of the plots being either located on stand borders between clear-cuts and forest or in the clear-cut area.

NDVI, SR, and RSR all had fairly strong positive correlation with LAI but differed with respect to their predictive power as indicated by the sensitivity to changes in LAI (Fig. 4). NDVI correlated slightly better with LAI ($r^2 = 0.55$) than did SR ($r^2 = 0.52$) but it had a narrow range (0.64 to 0.89) across the range of LAI values (0.36 to 3.72). Nevertheless, in terms of LAI estimation, SR and NDVI had approximately the same standard errors of estimates (SEE), 0.49 and 0.48, respectively. Compared to the two other indices, RSR not only had the strongest correlation with LAI ($r^2 = 0.63$) and the smallest standard error of estimate (0.43), but also was the most sensitive to changes in LAI.

Homogeneous plots were identified using the criterion that the mean LAI of the plot deviated less than 10% from LAI obtained at the plot centre. For these 381 plots, RSR explained 75% of the variation in LAI and SEE was reduced to 0.33 (Fig. 5).

From the homogeneous plots, pure Scots pine or Norway spruce plots were picked out using the criterion that the stand density at the plot centre included less than 10% of any other tree species. The RSR-LAI relationships were somewhat different for pine and spruce, but the separation

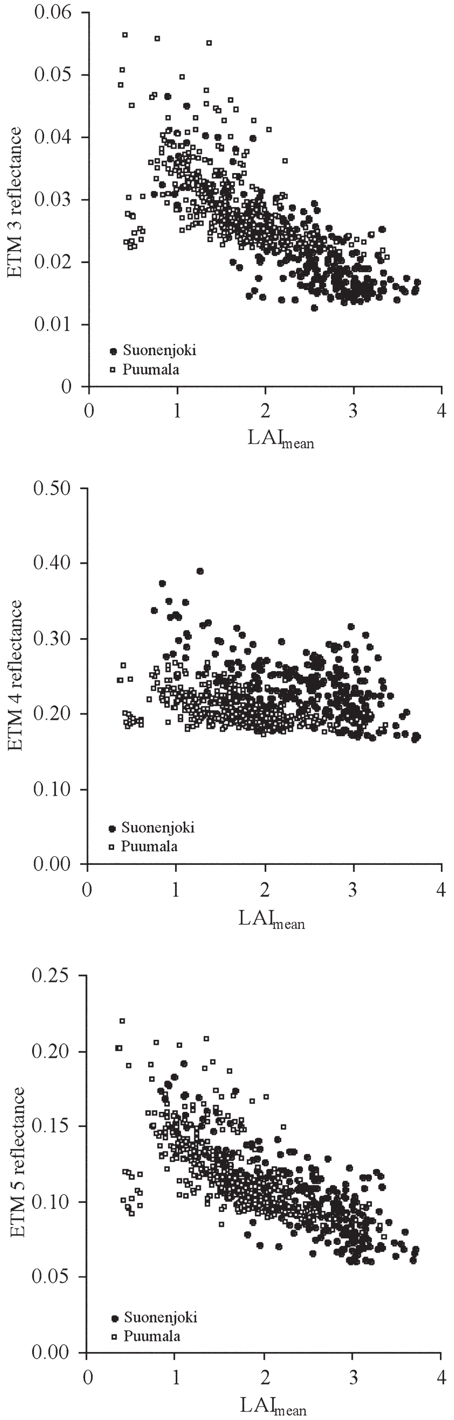

Fig. 3. Relationships of LAI with ETM 3, 4, and 5.

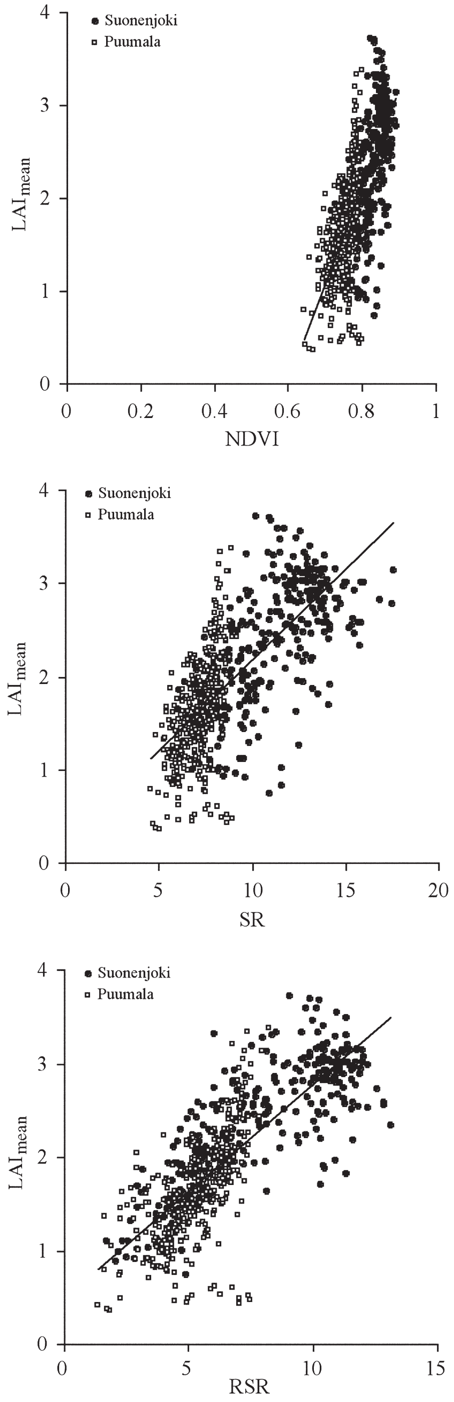

Fig. 4. Relationships of LAI with NDVI, SR and RSR.
NDVI: $LAI_{mean} = 10.36$ NDVI $- 6.17$, $r^2 = 0.55$, SEE $= 0.48$
RSR: $LAI_{mean} = 0.23$ RSR $+ 0.49$, $r^2 = 0.63$, SEE $= 0.43$
SR: $LAI_{mean} = 0.19$ SR $+ 0.24$, $r^2 = 0.52$, SEE $= 0.49$

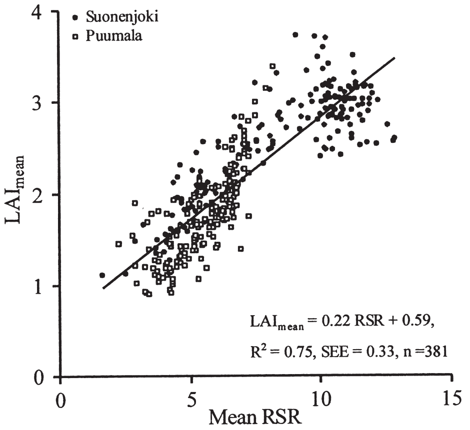

Fig. 5. RSR-LAI for homogeneous plots. Homogeneous plots were identified using the criterion that LAI_{mean} of the plot deviated less than 10% from LAI obtained at the plot centre.

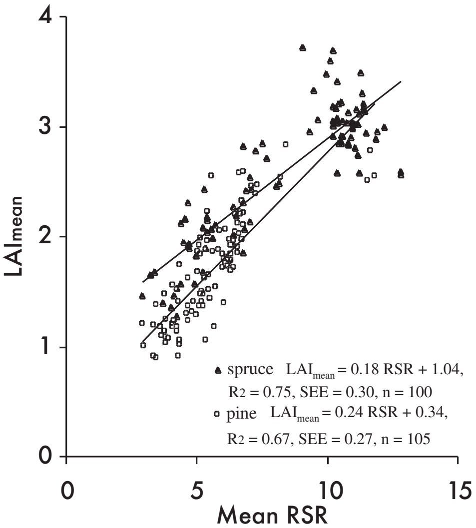

Fig. 6. RSR-LAI for pure pine and spruce plots. Pure plots were defined to have less than 10% of any other tree species in their stand density (at the plot centre).

between species did not improve correlation with LAI (Fig. 6).

The relationship between RSR and LAI derived for homogeneous plots using both sites (Fig. 5) was used to predict LAI at the two sites. Maps of measured and estimated values of LAI, produced by linear interpolation from each gridpoint

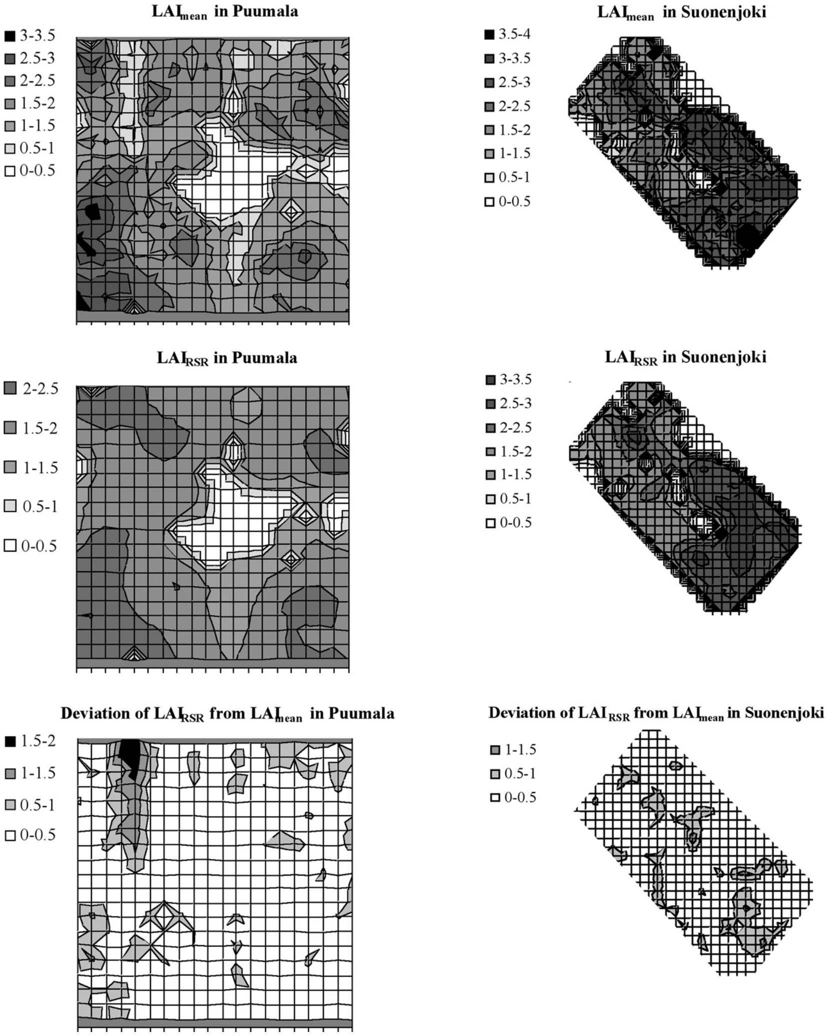

Fig. 7. Distributions of measured ($\mathrm{LAI}_{\mathrm{mean}}$) and estimated ($\mathrm{LAI}_{\mathrm{RSR}}$) LAI, and their difference over the Puumala and Suonenjoki sites.

in the four cardinal directions, are shown in Fig. 7 together with an absolute (LAI) value deviation map. When comparing LAI maps over both sites, the LAI estimated with RSR (denoted with $\mathrm{LAI}_{\mathrm{RSR}}$) depicts well the large scale variation in LAI. At the Suonenjoki site a more detailed patchiness of the area in terms of LAI was maintained in RSR-based LAI estimation than at Puumala, where the largest deviation between $\mathrm{LAI}_{\mathrm{mean}}$ and $\mathrm{LAI}_{\mathrm{RSR}}$ was 1.7.

4 Discussion

In this study, comprising an extensive data set, the reduced simple ratio (RSR) correlated better with LAI than did NDVI or SR. In contrast to the red-NIR based indices, the relationship between RSR and LAI unified data from the two study sites which were dominated by pine and spruce, respectively (Figs. 4–6). Support for that RSR serves to unify mixed forest species has been given earlier by Brown et al. (2000), Chen et al. (2002) and

Eklundh et al. (2003) (where, however, RSR did not perform well for pure deciduous stands). For predicting LAI on regional scales, SVIs with a reduced need for cover-type stratification are very desirable. Especially in countries like Finland, where the stands are typically quite small, the usefulness of a SVI for predicting (the small scale variation in) LAI relies on such unifying property.

The RSR-LAI relationship was good ($r^2 = 0.75$) for homogeneous plots at a spatial scale which corresponds to a typical area of stands in Finland (1 to 2 ha) (Fig. 5). Estimated values of LAI using RSR agreed well with the measured ones, and even rather small scale variation in LAI was captured, especially at the Suonenjoki site (Fig. 7). Surprisingly in general, the largest deviations between the estimated and measured LAI values (found in Puumala) were not observed at the borders of clear-cuts or sapling stands, but for instance at places where logging routes had been previously located. In other words, the performance of RSR was weaker at plots around which LAI were relatively constant but the reflectances heterogeneous due to a non-vegetation component (e.g. logging roads, rocks, large ditches). An interesting feature observed in the LAI deviation map of the Suonenjoki site is that the “errors” in the LAI_{RSR} (i.e. large deviations from LAI_{mean}) occur in general at plots where cutting waste had been left or where there was considerable topographical variation (e.g. a hill). It is reasonable to believe that such large deviations due to the non-vegetation components will usually be of small scale and influence only the satellite image (RSR) based LAI estimate of approximately one or two stands. This is an advantage of using a relatively small pixel size (e.g. Landsat ETM).

LAI values were not corrected for grouping due to the lack of some input parameters required by the procedure used earlier (Stenberg et al. 2003). Thus, in this study both measured and estimated values refer to an “effective LAI”, which is, depending on the stand density, in the order of 1.5 to 2 times smaller than the true LAI for Scots pine and Norway spruce stands (Rautiainen 2002, Stenberg et al. 2003). It should be recognised that the measured LAI (0.36 to 3.72) would then correspond to true LAI ranging approximately from 0.5 to 7.5, which covers most part of the variation in LAI in Finnish forests. However, as noted earlier based on the results of Eklundh et al. (2003), there is no reason to correct optically estimated LAI values prior to regressing them with reflectance data (SVIs), but this can be done afterwards if needed. Especially when LAI estimation is done for monitoring purposes, in other words to observe the changes in LAI, it may not be necessary to know the true LAI – an estimate of the effective LAI may suffice.

In addition to SVIs, another approach to LAI estimation from satellite data is physical reflectance models. Physically based theoretical models have the advantage over empirical (regression) models that they are (at least in principle) less site specific. Application of such models, however, is often limited by the requirements of fairly large homogeneous areas and/or additional (unknown) input data, and use of SVIs is often the only option. On the other hand, even though SVIs are considered to diminish to a certain extent the background (soil and understorey) effect in canopy LAI estimation, the fact that the relative contributions of the ground and tree layer components differ along with sensor and sun angles should be recognised. In practice, this means that the derived RSR-LAI regressions are sensor-dependent in two ways: they depend on solar angle and band width. In other words, a regression developed for one sensor may not be directly applicable, at least without further study, to another instrument.

The performance of RSR was in this study remarkably good: variation in LAI over the sites was captured well by the LAI-RSR regression and the small scale trouble areas (large deviations between measured and predicted LAI) could be identified to contain a disturbance, an abnormality from the basic, “pure” forest structure. Thus it is reasonable to say on the basis of our results that exploring the applicability of different SVIs alongside developing physical reflectance models remains an important field of research.

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