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Satellite remote sensing for estimating leaf area index, FPAR and primary production

A literature review

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March 2004

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Keywords: Satellite remote sensing, Vegetation index, NDVI, Leaf area index, LAI, FPAR, APAR, Primary production, Forsmark, Oskarshamn, Vegetation data, Biosphere, Surface, Ecosystem.

Abstract

Land vegetation is a critical component of several biogeochemical cycles that have become the focus of concerted international research effort. Most ecosystem productivity models, carbon budget models, and global models of climate, hydrology and biogeochemistry require vegetation parameters to calculate land surface photosynthesis, evapotranspiration and net primary production. Therefore, accurate estimates of vegetation parameters are increasingly important in the carbon cycle, the energy balance and in environmental impact assessment studies. The possibility of quantitatively estimating vegetation parameters of importance in this context using satellite data has been explored by numerous papers dealing with the subject. This report gives a summary of the present status and applicability of satellite remote sensing for estimating vegetation productivity by using vegetation index for calculating leaf area index (LAI) and fraction of absorbed photosynthetically active radiation (FPAR). Some possible approaches for use of satellite data for estimating LAI, FPAR and net primary production (NPP) on a local scale are suggested. Recommendations for continued work in the Forsmark and Oskarshamn investigation areas, where vegetation data and NDVI-images based on satellite data have been produced, are also given.

Sammanfattning

Den terrestra vegetationen är en kritisk komponent i många biogeokemiska kretslopp, vilka har kommit att stå i fokus för samlade internationella forskningsinsatser de senaste åren /IGBP, 1990; Sellers och Schimel, 1993/. De flesta ekosystemproduktionsmodeller, kolbudgetmodeller och globalmodeller för klimat, hydrologi och biokemi behöver vegetationsdata för att fotosyntes, evapotranspiration och nettoprimärproduktion skall kunna beräknas /Running och Coughlan, 1988; Prince, 1991a; Running och Gower, 1991; Potter et al, 1993; Sellers et al, 1997/. Tillförlitliga vegetationsdata är därför mycket viktiga för beräkning av kolflöden, energibalans och miljöpåverkan /Tian et al, 2000/.

Möjligheterna att kvantitativt beräkna vegetationens produktivitet med hjälp av satellitdata har undersökts teoretiskt av /Sellers, 1985, 1987; Tucker och Sellers, 1986; Choudhury, 1987/, och har följts av många andra artiklar inom ämnesområdet. Intressanta parametrar i sammanhanget är ”leaf area index” (LAI), vilket är ett mått på mängden grön biomassa per ytenhet, och andelen absorberat fotosyntetiskt aktivt ljus (FPAR), vilket relaterar tillgängligt ljus för fotosyntes till mängd ljus som absorberats av växterna för fotosyntes. Ett flertal vegetationsindex som utnyttjar spektral information från radiometrar eller satelliter har föreslagits för att relatera uppmätt reflekterat ljus till LAI och FPAR. Avsikten med föreliggande rapport är att sammanfatta det aktuella forskningsläget och möjligheterna att med hjälp av fjärranalys beräkna LAI, FPAR och primärproduktion, samt att ge rekommendationer för fortsatt arbete inom SKBs undersökningsområden i Forsmark och Oskarshamn.

Föreliggande litteraturstudie är en fortsättning på den satellitbildsbaserade vegetationskartering som utförts för SKB över Forsmarks och Oskarshamns undersökningsområden /Boresjö Bronge och Wester, 2003/. NDVI-bilder har också producerats över dessa områden, vilket beskrivs i kapitel 6.

Ett stort antal samband har upprättats mellan vegetationsindex och LAI. Man kan urskilja två huvudangreppssätt för att uppskatta LAI med hjälp av fjärranalys: användande av avancerade modeller baserade på ljusspridningsteori samt användande av empiriskt upprättade samband. Beräkning av LAI för en vegetationsyta på basis av optisk fjärranalys är inte enkel, även om den utgör enda möjligheten till att erhålla den rumsliga fördelningen av LAI. Eftersom flera faktorer påverkar den spektrala reflektionen från en vegetationsyta/krontak kan inte ett unikt samband mellan LAI och vegetationsindex förväntas gälla överallt och vid alla tidpunkter ens för samma sensor. En av de mest allvarliga begränsningarna är att indexen snabbt mättas och blir okänsliga för variationer i LAI vid höga LAI-värden.

Beräkning av LAI med satellitdata fordrar fältdata för kalibrering, validering och för test av systematiska fel. Det är också uppenbart att vegetationsegenskaper och bakgrund signifikant påverkar sambandet mellan vegetationsindex och LAI /Turner et al, 1999/. Detta antyder att det för att erhålla lokal tillförlitlighet i härledningen av LAI är önskvärt att stratifiera med avseende på vegetationstyp (t ex struktur och successionsstadium) samt att välja optimalt vegetationsindex för varje stratum.

Sambandet mellan FPAR och vegetationsindex beräknat för krontaket har visats empiriskt och teoretiskt i flera undersökningar. Sambandet NDVI-FPAR är linjärt i de flesta fall, med undantag för krontak med ”ljus” NDVI-bakgrund (kraftigt reflekterande fältskikt). Vidare är sambandet oberoende av typ av marktäcke, bladyta och variationer i bladorientering och optiska egenskaper. Å andra sidan är sambandet känsligt för bakgrund, atmosfärsförhållanden och effekter som härrör från att vegetationen kan ha olika reflektionsegenskaper

beroende på ljusets infallsvinkel i förhållande till sensorn. Ett enkelt linjärt samband för att relatera FPAR till NDVI uppmätt vid krontaket har föreslagits av /Myneni och Williams, 1994/. Sambandet är giltigt för solhöjder över 30°, bakgrund och jordarter som inte reflekterar allt för mycket (NDVI ca 0,12) och för atmosfärsförhållanden med ”optical depth” mindre än 0,65 vid 0,55 μm.

Nettoprimärproduktion (NPP) för terrestra biom kan beräknas med stöd av fjärranalys och ”light use efficiency”-modeller /se t ex Field et al, 1995/ eller med hjälp av mer komplexa processmodeller /Running och Coughlan, 1988; Liu et al, 1997/.

Grunden för ”light use efficiency”-modellerna är antagandet att växternas fotosyntetiska bindning av kol är proportionell mot absorberad mängd fotosyntetiskt aktivt ljus, och att andelen fotosyntetiskt aktivt ljus som absorberas av växterna (FPAR) kan mätas med fjärranalys. Flera parametrar påverkar dock hur effektivt växterna kan tillgodogöra sig ljuset, bl a vatten- och näringstillgång. Vanliga angreppssätt är därför att använda medelvärden för kolallokering eller ljusanvändningseffektivitet för de stora vegetationsregionerna som korrigerats för vatten och näringstillgång.

Processmodeller simulerar de biologiska processer som påverkar nettoprimärproduktionen som fotosyntes, respiration och transpiration. Dessa modeller är dock ofta sofistikerade och kräver stora mängder ingångsdata.

I rapporten presenteras några tänkbara tillvägagångssätt för att använda satellitdata för att beräkna LAI, FPAR och NPP på lokal skala.

Contents

1 Introduction

1.1 Background

Land vegetation is a critical component of several biogeochemical cycles that have become the focus of concerted international research effort /IGBP, 1990; Sellers and Schimel, 1993/. Most ecosystem productivity models, carbon budget models, and global models of climate, hydrology and biogeochemistry require vegetation parameters to calculate land surface photosynthesis, evapotranspiration and net primary production /Running and Coughlan, 1988; Prince, 1991a; Running and Gower, 1991; Potter et al, 1993; Sellers et al, 1997/. Therefore, accurate estimate of vegetation parameters are increasingly important in the carbon cycle, the energy balance and environmental impact assessment studies /Tian et al, 2000/.

Of the various techniques that might be considered for the studies of vegetation processes, only satellite remote sensing offers a realistic possibility to obtain the requisite data globally because of the large extent, strong spatial and temporal dynamics, and logistical inaccessibility of the vegetation /Cihlar et al, 1991/. Much attention has therefore been given to vegetation studies in satellite data since the launch of the first Earth resource satellite, Landsat 1, in 1972. Especially the 1 km data provided by the Advanced Very High Resolution Radiometer (AVHRR) have been of interest in a global perspective, since daily images of entire landmasses can be obtained to acceptable data rates.

The possibility of quantitatively estimating vegetation productivity using satellite data has been explored theoretically by /Sellers, 1985, 1987; Tucker and Sellers, 1986; Choudhury, 1987/, and others, and has been followed by numerous other papers dealing with the subject. Parameters of interest in this context are leaf area index (LAI), which is a quantitative measure of the amount of live green biomass, and the fraction of absorbed photosynthetically active radiation (FPAR), which is an essential parameter relating the available visible solar radiation to its absorption by chlorophyll for plant photosynthesis. Several vegetation indices, using spectral information from radiometers or satellites, have been proposed for relating measured reflected radiation to LAI and FPAR. The aim of this review is to give a summary of present status and applicability of satellite remote sensing for estimating vegetation productivity, and to give recommendations for continued work in the two SKB study areas Forsmark and Oskarshamn, where satellite-data based methods previously have been used for production of a vegetation database /Boresjö Bronge and Wester, 2003/.

Two NDVI-images have also been produced for Forsmark and Oskarshamn. A description of how the images are generated is given in Chapter 6.

1.2 Some definitions

Below is given some definitions of important parameters relating to the subject dealt with in the review.

Leaf area index (LAI): LAI is a quantitative measure of the amount of live green leaf material present in the canopy per unit ground surface. It is defined as half the total green leaf area (one-sided area for broad leaves) per unit ground surface /Chen and Black, 1992/. LAI describes a fundamental property of the plant canopy in its interaction with the atmosphere, especially concerning radiation, energy, momentum and gas exchange /Monteith and Unsworth, 1990/. Leaf area plays a key role in the absorption of radiation, in the deposition of photosynthates during the diurnal and seasonal cycles, and in the pathways of rates of biogeochemical cycling within the canopy-soil system /Van Cleve et al, 1983; Bonan, 1995/.

Net primary production (NPP): NPP refers to the net carbon uptake by the ecosystem in one year, and is a fundamental property describing ecosystem performance (http://www.wmo.ch/web/gcos/terre/variable/npprod.html). It is defined as the difference between total carbon uptake through photosynthesis and losses (through maintenance or growth respiration). NPP is a sum of two components, above (ANPP) and below (BNPP) ground net primary production. Because of its direct relationship to atmospheric CO_2 it plays a strong role in the global climate system. Seasonally it accounts for the latitudinal dependence of the CO_2. On the annual basis, it accounts for the land proportion of the carbon sink /Tans et al, 1990/.

Net ecosystem productivity (NEP): Like NPP, NEP includes the annual sum of carbon fixed by daytime photosynthesis and of carbon released by night time respiration of fixed carbon. Unlike NPP, NEP also includes carbon released by maintenance respiration inside plants, by microbial respiration of organic compounds in dead plants and branches, in surface litter, and in soils, and respiration/loss of grazed living plant material by other respiring animals (http://www.wmo.ch/web/gcos/terre/variable/npprod.html). Thus, NEP is a measure of the residual annual carbon incremented to the long-term carbon stocks, and as such, a critical variable to determining long-term behavior of the terrestrial carbon cycle.

PAR: Photosynthetically active radiation (0.4–0.7 µm, visible wavelengths). PAR is the part of the radiation that is able to penetrate the upper epidermal surface of leaves /Tucker and Sellers, 1986/.

FPAR (or **FAPAR, f_{APAR}):** Fraction of PAR absorbed by vegetation /Chen, 1996; Knyazikhin et al, 1998; Gower et al, 1999; Tian et al, 2000, among others/. /Myneni and Williams, 1994/ define FAPAR as fraction of incident PAR absorbed by the photosynthesising tissue in a canopy.

APAR: The amount of absorbed photosyntethically active radiation /Prince, 1991a/. APAR is calculated as the product of PAR surface irradiance and FPAR ($APAR = PAR_{si} \cdot FPAR$) /Field et al, 1995/.

FIPAR/f_{IPAR}: Fraction intercepted photosyntethically active radiation /Gower et al, 1999/.

LUE: Light use efficiency /Gower et al, 1999/. The efficiency by which APAR is converted to plant biomass increments.

1.3 Satellites

A selection of satellites and data set available for Earth observation is given in Table 1-1. The information is compiled from information of current and future sensor systems given by the Center for Health Applications of Aerospace Related Technologies (CHAART) which is part of the Ecosystem Science and Technology (ECOSAT) Branch of the Earth Science Division at the NASA Ames Research Center.

Table 1-1. Selection of satellites and data set available for Earth observation (http://geo.arc.nasa.gov/sge/health/sensor/cfsensor.html).

Mission	Country	Launch Year	Instrument	Spatial Resolution • (meters, at nadir) PAN	VNIR	SWIR	TIR	SAR/ band	Swath • (km)	Repeat Cycle (day)
Ikonos	USA: Space Imaging	1999	Ikonos	1	4				300	11
Quickbird 2	USA: DigitalEarth	2001	Quickbird	1	4				22	1–5
Orbview-3	USA: Orbimage	(TBD)	Orbview-3	1	4				8	3
SPOT-2	France	1990	HRV	10	20				60	1–26
SPOT-4	France	1998	2xHRV-IR Vegetation	10	10, 20 1000	10, 20 1000			60 2200	3 1
SPOT-5a / SPOT-5b	France	2002/ (2004)	HRG Vegetation	5	10 1000	20 1000			60 2200	3 1
Landsat 5	USA	1984	TM		30	30	120		185	16
Landsat 7	USA	1999	ETM+	15	30	30	30		185	16
Resource21	USA	(2005)	Resource21		10	20	100		?	7
CBERS	China/ Brazil	1999	CCD IR-MSS WFI	20 80	20 260	20 80 260	 80		120 120 900	3–26 26 3–5
ARIES-1	Australia	(TBD)	ARIES	10	30	30			15	7
IRS-1A / IRS-1B	India	1988/ 1991	LISS I LISS 2		72 36				148 74/ 74x2	22 22
IRS-1C / IRS-1D	India	1995/ 1997	PAN LISS 3 WiFS	6	 23 188	 70 188			70 142–148 774	5–24 24 5–24
Terra (EOS AM-1)	USA/ Japan	1999	ASTER MISR MODIS		15 240, 480, 960, 1900 250, 500, 1000	20 500, 1000	90 1000		60 370–408 2300	16 2–9 2
Aqua (EOS PM-1)	USA	2002	MODIS		250, 500, 1000	500, 1000	1000		2300	2
EOS AM-2	USA	(2004)	MISR MODIS SAR-70 SLR-3		240, 480, 960, 1900 250, 500, 1000	 500, 1000	 1000	 30/L 5–700/X	370–408 2300 120–170 450	9 2 3 3
NOAA-10	USA	1985	AVHRR		1000	1000	1000		3000	0.5
NOAA-12	USA	1991	AVHRR/2		1100	1100	1100		3000	0.5
NOAA-14	USA	1994	AVHRR/2		1000	1000	1000		3000	0.5
NOAA-L / NOAA-M / NOAA-N	USA	2000/ 2002/ (2003)	AVHRR		1100	1100	1100		3000	0.5

2 Spectral properties of vegetation

The spectral radiance from plant canopies in the 0.4–2.5 µm region provides the basis for passive remote sensing of vegetated areas and can be measured from ground, with airborne or spaceborne sensors /Tucker and Sellers, 1986/.

In the photosynthesis process green vegetation uses light energy to produce carbohydrates from CO_2 and water and release O_2. Photosynthetically active radiation (PAR) (0.4–0.7 µm) is able to penetrate the upper epidermal surface of leaves /Gates et al, 1965; Knipling, 1970; Woolley, 1971; Gausman, 1974/, and is absorbed strongly by the plant pigments present (chlorophyll a, chlorophyll b, carotenoids). Thus, absorption is high in the 0.4–0.7 µm region and reflectance and transmittance low. In the near-infrared part of the spectrum (0.7–1.3 µm), scattering by the structures within the leaves causes a high reflectance and transmittance since little absorption occurs /Tucker and Sellers, 1986/. While liquid water is transparent to the PAR wavelengths, it is a strong absorber in the 1.3–2.5 µm region /Curcio and Petty, 1951/. The water present in leaf tissues therefore causes absorption in this region. Figure 2-1 shows the coefficients of absorptance for chlorophyll a, chlorophyll b, the carotenoid lutein, and liquid water.

The in situ plant-canopy reflectance is influenced by the soil background, especially for sparse canopies /Colwell, 1974; Ezra et al, 1984; Huete et al, 1984, 1985; Elvidge and Lyon, 1985/. Therefore, remote-sensing studies of vegetation normally use specific wave-lengths selected to provide a strong signal from the vegetation and also have a large spectral contrast from most background materials.

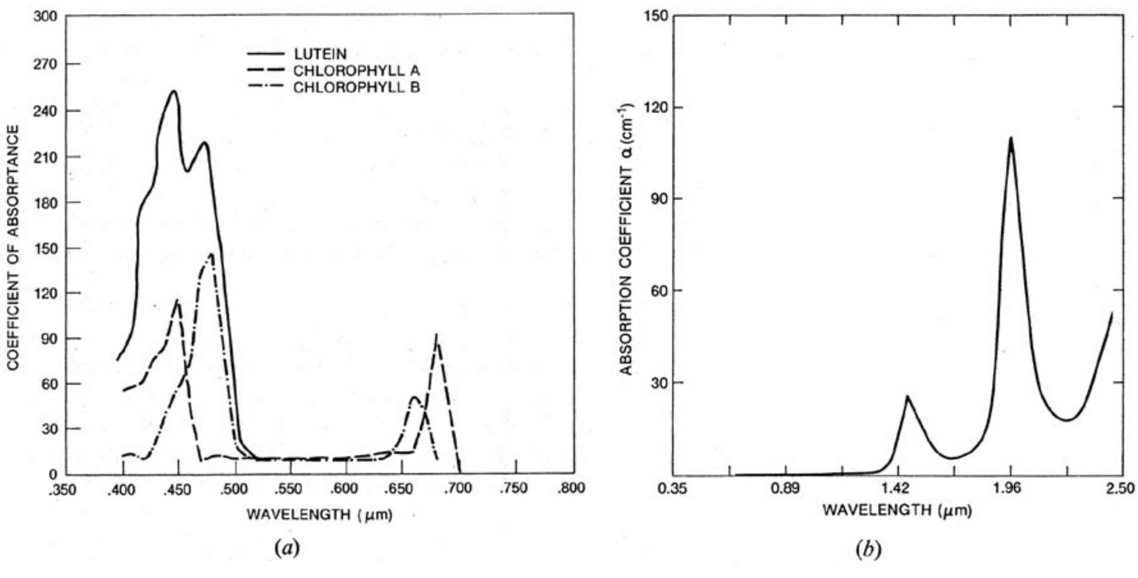

Figure 2-1. *Coefficients of absorptance for chlorophyll a, chlorophyll b, and lutein (a) and pure liquid water (b). From /Tucker and Sellers, 1986/.*

/Tucker, 1978/ has proposed five primary and two transition regions between 0.4–2.5 μm where differences in leaf optical properties (scattering and absorption) and the background optical properties control plant-canopy spectral reflectance (Figure 2-2). The regions are: (1) 0.4–0.5 μm, where strong spectral absorption by the chlorophylls and the carotenoids occurs; (2) 0.5–0.62 μm, where reduced levels of chlorophyll absorption occur (i.e. why green vegetation to our eyes appears “green”); (3) 0.62–0.7 μm, where strong chlorophyll absorption occurs; (4) 0.70–0.74 μm, where strong absorption ceases; (5) 0.74–1.1 μm, where minimal absorption occurs and the leaf scattering mechanisms result in high levels of spectral reflectance; (6) 1.1–1.3 μm, where the liquid-water coefficients of absorption increase from close to 0 at 1.1 μm to values of 4 at 1.3 μm; and (7) 1.3–2.5 μm, where absorption by liquid water occurs.

Thus, it can be concluded that information about vegetation canopies, potentially available from 0.4–0.7, 0.74–1.1 and 1.3–2.5 μm, is related respectively to the plant pigments present, the projected green-leaf density and the liquid water present /Tucker and Sellers, 1986/.

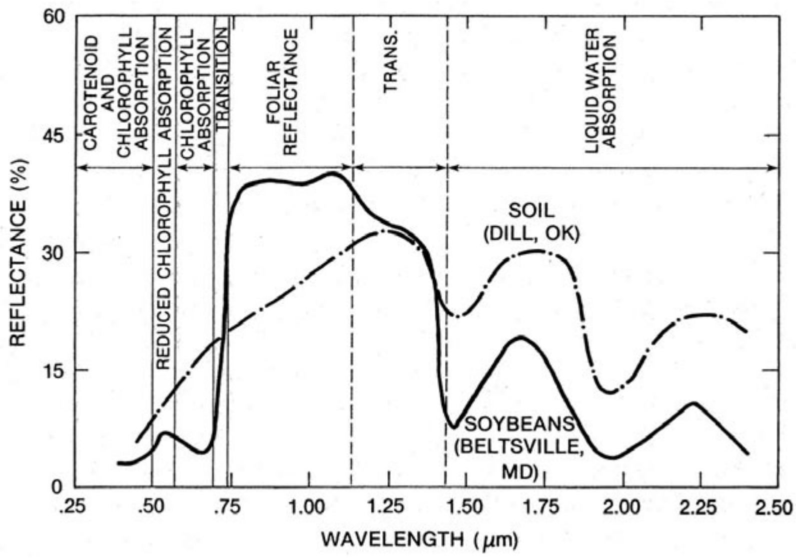

__Figure 2-2.__ Delineation of the 0.4–2.5 μm region into spectral intervals where different biophysical properties of green vegetation control the reflectance of incident solar irradiance from the vegetation in question. Sample spectral reflectance curves for green vegetation and soil are also included to illustrate why some wavelengths have greater spectral contrast than others. From /Tucker and Sellers, 1986/.

3 Vegetation indices

Most vegetation indices combine information contained in two spectral bands: red and near-infrared. These indices are established in order to minimise the effect of external factors on spectral data and to derive canopy characteristics such as leaf area index (LAI) and fraction of absorbed photosynthetic active radiation (FPAR) /Baret and Guyot, 1991/.

The most commonly used indices to derive LAI and other surface parameters from space-borne and airborne remote sensing data are the simple ratio (SR) /Jordan, 1969/ and the normalised difference vegetation index (NDVI) /Rouse et al, 1974/. These indices have been found to be well correlated with various vegetation variables including green leaf area /Holben et al, 1980; Asrar et al, 1984, 1985b; Hatfield et al, 1985; Clevers, 1989/, standing biomass /Tucker, 1979; Elvidge and Lyon, 1985/, photosynthetic activity /Hatfield et al, 1984; Sellers, 1985, 1987; Choudhury, 1987/ and productivity /Asrar et al, 1985a/.

SR and NDVI combine red (r) and near-infrared (nir) reflectances or radiances in the form of ratios:

$$SR = nir/r$$

$$NDVI = (nir - r)/(nir + r)$$

SR and NDVI enhance the contrast between soil and vegetation and minimise the effects of illumination conditions. But, they are sensitive to optical properties of soil background /Elvidge and Lyon, 1985; Huete et al, 1985/. Several indices therefore have been proposed to minimise the effects of soil background, e.g. the perpendicular vegetation index (PVI) /Richardson and Wiegand, 1977/, the weighted difference vegetation index (WDVI) /Clevers, 1986, 1989/, the soil adjusted vegetation index (SAVI) /Huete, 1988/, and the transformed soil adjusted vegetation index (TSAVI) /Baret et al, 1989/.

The PVI index represents the orthogonal distance from a point corresponding to canopy reflectance to the soil line in the red-near-infrared space. The soil line is the relation between red and near-infrared for different soils when LAI = 0. For a given soil, the red (r_g) and near-infrared (nir_g) reflectances are related by the equation of the soil line:

$$nir_g = a \cdot r_g + b$$

The parameters *a* and *b* vary slightly among soils /Huete et al, 1984/. PVI can be expressed as a linear combination of the nir and r reflectances for the canopy:

$$PVI = 1/\sqrt{(a^2 + 1)}\ (nir - a \cdot r - b)$$

However, it was shown that also the PVI was affected by the optical properties of the soil background /Huete et al, 1985; Huete, 1988; Major et al, 1990/. For a given quantity of incomplete vegetation cover brighter soils result in higher index values. For this reason some new indices, which are less influenced by the soil brightness, have been proposed /Clevers 1986, 1988, 1989; Huete, 1988, 1989; Baret et al, 1989; Major et al, 1990/. The simplest is proposed by /Clevers, 1986, 1989/, who introduced the weighted difference vegetation index (WDVI).

$$WDVI = nir - a \cdot r$$

The index is related to the PVI according to the following:

$PVI = 1 / \sqrt{(a^2 + 1)}\ (WDVI - b)$

The soil adjusted vegetation index (SAVI) proposed by /Huete, 1988/ is derived from the NDVI:

SAVI = (nir–r)/(nir+r+L)(1+L)

The constant L is introduced in order to minimise soil-brightness influences. It can vary from zero to infinity as a function of the canopy density. If L = 0 (dense vegetation), SAVI is equivalent to NDVI and if L tends towards infinity (bare soil), it is equivalent to PVI /Baret and Guyot, 1991/. SAVI is an exact solution for bare soil only when the soil line parameters are $a = 1$ and $b = 0$. Since this is not generally the case, /Baret et al, 1989/ proposed the transformed soil adjusted vegetation index (TSAVI). TSAVI measures the angle between the soil line and the line which joins the vegetation point and a point (S) belonging to the soil line, the abscissa of which is –X. The following equation is an improved version of the initial definition given by /Baret et al, 1989/:

$TSAVI = a \cdot (nir - a \cdot r - b) / [a \cdot nir + r - ab + X \cdot (1 + a^2)]$
/Baret and Guyot, 1991/

where *a* and *b* are the parameters of the soil line and X corresponds to the negative abscissa of the point S. The value of X has been adjusted to minimise soil effects (X = 0.08). TSAVI is multiplied by the parameter *a* to give a vegetation index less dependent on soil parameters (*a*,*b*) for high canopy densities (nir >> r). TSAVI equals 0 for bare soil and is close to 0.70 for very dense canopies. For $a = 1$ and $b = 0$, TSAVI is equivalent to NDVI /Baret and Guyot, 1991/.

Indices have also been proposed that correct for the atmospheric effects on data when measuring from the top of the atmosphere. One such index is the Atmospherically Resistant Vegetation Index (ARVI), proposed by /Kaufman and Tanré, 1992/ which incorporates a self-correction process for the atmospheric effect at red wavelength by utilising the radiance difference between blue and red wavelengths. To specifically correct for atmospheric effects in AVHRR data, the Global Environment Monitoring Index (GEMI) was developed /Pinty and Verstraete, 1992/. GEMI exhibits a high atmospheric transmissivity, insensitivity to soil reflectance, with the exception of very bright soils, and is empirically representative of vegetation properties in a manner similar to the other indices.

4 Vegetation indices for estimation of LAI, FPAR and primary production

4.1 Leaf area index (LAI)

Leaf area index (LAI), or half the total green leaf area per unit ground surface, is a key biophysical variable influencing land surface photosynthesis, transpiration, and energy balance /Bonan, 1995/.

A large number of relationships have been established between vegetation indices and LAI, mostly for crops and grasslands /e.g. Asrar et al, 1985b; Best and Harlan, 1985; Curran and Williamson, 1987; Wanjura and Hatfield, 1987; Wiegand et al, 1988; Shibayama and Akiyama, 1989; Friedl et al, 1994; Goetz, 1997/, but also for other vegetated surfaces such as shrublands /Law and Waring, 1994/, broadleaf forest /Badhwar et al, 1986a**;** Fassnacht et al, 1997/, coniferous forest /Badhwar et al, 1986b; Running et al, 1986; Peterson et al, 1987; Spanner et al, 1990a,b, 1994; Chen and Cihlar, 1996; Turner et al, 1999; Eklundh et al, 2001/, and mixture of vegetation types /White et al, 1997/. Investigations on relationships between LAI and satellite data for coniferous forests in Scandinavia include /Gemmel and Varjo, 1999; Nilson et al, 1999/ and /Eklundh et al, 2001/.

4.1.1 Parameters influencing the relationships

Most vegetation indices are dependent on internal factors such as canopy geometry (leaf angle distribution function, row orientation, and spacing), leaf and soil optical properties, or external factors such as sun position and nebulosity to provide good estimates of LAI /Baret and Guyot, 1991; Williams, 1991; Yoder and Waring, 1994/.

The sensitivity of vegetation indices to canopy geometry has been shown by /Jackson et al, 1979; Chance, 1981; Kollenkark et al, 1982; Aase et al, 1984; Jackson, 1986/ and /Chen, 1996/, among others. Within tree crowns, variability is introduced by leaf clumping of various types which causes shading at a fine spatial scale, and the contribution of woody material to total reflectance /Guyot et al, 1989; Williams 1991; Huemmrich and Goward, 1997/. At the multitree scale, heterogeneity in tree height and the number and size of tree gaps influences reflectance /Guyot et al, 1989; Cohen et al, 1990; Cohen and Spies, 1992; Leblon et al, 1996/.

The two most important parameters affecting the radiation regimes in plant canopies are the foliage angular distribution and the foliage spatial distribution /Chen, 1996/. The foliage angle distribution determines the variation of canopy gap fraction with zenith angle. The foliage spatial distribution determines the amount of radiation transmitted through the canopy for the same LAI. The clumping of foliage in conifer stands for example does not only result in more radiation transmission (larger gap fraction) than the random case, but it also alters the gap size distribution.

The sensitivity of vegetation indices to background reflectance variations (soil and litter) has been shown by /Kanemasu, 1974; Vanderbilt et al, 1981; Huete et al, 1985; Huete, 1987a; Huete and Jackson, 1987/, and /Baret and Guyot, 1991/, among others. /Baret and Guyot, 1991/ analysed the relationship with LAI for four indices (NDVI, PVI, SAVI, TSAVI). The sensitivity analysis showed that NDVI and, to a lesser degree, PVI, are strongly affected by the variation of soil optical properties, particularly for low vegetation cover, whereas SAVI and TSAVI strongly reduced the noise for low leaf area indices (LAI < 2–3). On the contrary, TSAVI, which was the best vegetation index for lower LAI, introduced the largest noise for large LAI because it reached its saturation level before the others (except NDVI).

In applications focused on overstory LAI variability in reflectance from understory vegetation can likewise be problematic /Franklin, 1986; Spanner et al, 1990a; Chen and Cihlar, 1996; Myneni et al, 1997/. For boreal forests, /Chen and Cihlar, 1996/ conclude that the major problem in deriving LAI from NDVI is the contribution from the understory.

Additional factors potentially altering vegetation indices independently of LAI concern sun-surface-sensor geometry and atmospheric scattering and absorption of radiation /Brach et al, 1981; Jackson et al, 1983; Asrar et al, 1985b; Holben et al, 1986; Shibayama et al, 1986; Huete, 1987b; Meyer et al, 1993; Myneni and Asrar, 1994; Deering et al, 1994; Chen and Cihlar, 1996/. Satellite-data derived indices must therefore be based on data corrected for atmospheric and bidirectional effects.

4.1.2 Saturation of the indices

For crops the indices generally approach a saturation level asymptotically for LAI ranging from 2 to 6, depending on the type of vegetation index used, the crop studied, and experimental conditions /Daughtry et al, 1980; Chance, 1981; Ahlrichs and Bauer, 1983; Best and Harlan, 1985; Wanjura and Hatfield, 1987/. For coniferous forest /Chen and Cihlar, 1996/ conclude that compared with similar relationships for cropland or grassland, NDVI derived from Landsat TM for boreal forests does not show an obvious saturation point with increasing LAI. Since, conifer canopies are highly clumped, they do not cover as much ground surface as agricultural crops and grasses with the same LAI, and therefore in the usual range of LAI from 1 to 5, the relationship is essential linear. Similar findings are reported by /Peterson et al, 1987/ who studied the relationship between airborne Thematic Mapper (ATM) data and LAI for a transect of temperate forest stands in Oregon. They found that the LAI to near IR/red relationship slowly become asymptotic, reaching a saturation level at a LAI of 10, more than twice as high as values reported for crop and grass communities. NDVI of leaf canopies such as grasses and crops always tends to be higher than forest canopies with similar LAI, because the trunks and branches in the latter tend to decrease near-infrared scattering, and therefore lower NDVI values /Myneni et al, 1997/. /Turner et al, 2000/ report similarly increasing SR, NDVI and SAVI-values with increasing LAI at low to mid LAIs values (LAI < 5) for studied vegetation types (grassland, shrub, broadleaf and conifeous forest). For all but the coniferous forest sites, sensitivity of the vegetation indices was low at LAI values above 5. In coniferous forests, the vegetation indices decreased at the highest LAI values because of decreasing near-infrared reflectance associated with the complex canopy in these mature to old-growth stands.

Investigations on the relationship between Landsat ETM+ sensor data (Landsat 7) and LAI in a boreal coniferous forest in Sweden have been carried out by /Eklundh et al, 2001/. Simulation of stand reflectance in the Landsat ETM+ bands, using a canopy reflectance model, showed that the response to changes in LAI was strongest in the visible bands, particularly channel 3 (red). Only weak response was noted in the near infrared band and for some vegetation indices (simple ratio index (SR) and NDVI). The strongest empirical relationship was obtained between estimated LAI and ETM+ channel 7 (mid-infrared). Modelled change in NDVI and SR with increasing LAI , where both LAI and stand density were changed, showed an increase up to 4–5 LAI, thereafter a decrease.

In a global perspective, /Myneni et al, 1997/ states that the relationship between NDVI and LAI is nonlinear and exhibits considerable variation among the cover types. For vertically inhomogeneous land covers such as savanna and forests the relationship is strongly dependent on the understory leaf area index. In forest canopies with a dense understory there is practically no sensitivity in NDVI to overstory LAI.

According to /Baret and Guyot, 1991/ the variation of a vegetation index (VI), as a function of LAI, can be expressed by a modifed Beer's law:

$$VI = VI_\infty + (Vi_g - VI_\infty) \cdot \exp(-K_{VI} \cdot LAI)$$

where

Vi_g = vegetation index corresponding to that of the bare soil,
VI_∞ = asymptotic value of VI when LAI tends towards infinity (practically this limit is always reached for LAI greater than 8.0),
K_{VI} = coefficient which controls the slope of the relationship (equivalent to an extinction coefficient).

The K_{VI} parameter represents the relative increase in VI due to elementary increase in LAI. It is called extinction coefficient by analogy to the classical Beer's law where the extinction (or absorption) coefficient describes the relative variation of a diffuse medium's transmission when its thickness is submitted to an elementary increase /Baret and Guoyt, 1991/. In the same way the product $K_{VI} \cdot LAI$ is analogue to an optical thickness. The parameters VI_∞ and K_{VI} depend on irradiance and view geometries and on leaf inclination.

4.1.3 LAI measurements on ground

LAI estimation from satellite data requires ground data for validation and test for bias. Direct measurement approaches of LAI include area harvest, application of allometric equations to stand diameter data, and leaf litterfall /Gower et al, 1999/. Area harvest involves the periodic destructive sampling of vegetation in plots during the growing season. The harvest approach is most appropriate for short-stature ecosystem such as grassland, agricultural crops and tundra. For forest, leaf area index can be estimated from allometric relationships applied to each tree surveyed in randomly located plots in the community of interest. Allometry is the relationship between the mass or area of a part (e.g. leaf mass or area), or all of an organism, and an independent variable /Gower et al, 1999/. The dependent variable is indirectly estimated because it is difficult, and often laborious, to measure. The independent variable commonly used to estimate leaf mass or area is stem diameter or sapwood cross section. A detailed description of the field methods used to destructively harvest trees to determine the mass and area of the biomass components is provided by /Gower et al, 1992/ and /Gower et al, 1997/.

The allometric relationship is often described as follows:

$$\text{Log } M_D \text{ or } \log A = a+b(\log D)$$
/Gower et al, 1999/

Where log is the natural or $base_{10}$ logarithmic transformation, M_D or A is dry mass or area, respectively, of a plant part, D is stem diameter, usually at breast height, an *a* and *b* are regression coefficients.

The predicted value derived from the equation has a small downward bias because of the logarithmic transformation. All allometric equations should therefore be corrected for logarithmic bias using the following equation /Sprugel, 1983/:

$$Cf = EXP((2.303 \cdot (MSE^{0.5}))^2/2)$$

Where CF = correction factor that the dependent variable should be multiplied by, and MSE = $\log_{10}$ transformed regression mean square error.

Allometric equations relating foliage mass to stem diameter (D) or sapwood cross sectional area (A_s) at breast height (1.37 m) can be used to directly estimate LAI if specific leaf area (SLA) is known, where SLA is the ratio of fresh foliage surface area to unit dry foliage mass. /Gower et al, 1999/ recommend scientists to report SLA on the basis of half total needle surface area, since one half the total leaf area, is the appropriate parameter for radiation transfer models.

There are several publications presenting allometric relationships between leaf area and stem diameter /e.g. Gholz et al, 1979; Gower, 1987/. /Marklund, 1988/ gives allometric equations between needle biomass and stem diameter for Scotch Pine (*Pinus sylvestris*) and Norwegian Spruce (*Picea abies*). However, using general allometric equations to estimate LAI for a specific stand can result in moderate to large errors because several biotic and abiotic factors, such as tree size, nutrient and water availability, shade-tolerance, and variability in leaf longevities, influence the allometry coefficients /Grier and Logan, 1977; Grier and Milne, 1981; Brix and Mitchell, 1983; Grier et al, 1984; Marshall and Waring, 1986; Chapman and Gower, 1991; Gholtz et al, 1991; Gower et al, 1992, 1993a,b, 1997; Kloeppel, 1998; Vogel and Gower, 1998/. The most important criterion to consider when selecting allometric equations is correctly matching the plant species and size /Gower et al, 1999/.

In recent years much emphasis has been placed on using indirect optical measurement techniques to measuring the canopy gap fraction to estimate LAI of vegetation canopies. For canopies that exhibit a random distribution of foliage elements (leaves, needles, stems, branches, shoots) LAI can be derived from the probability that a beam of direct radiation passes undisturbed through a canopy /Gower et al, 1999/. However, the penetration of direct beam radiation is influenced by the position, angle distribution, and the spatial relationship of the elements in the canopy /Norman and Jarvis, 1974; Welles, 1990; Chen and Black, 1992; Smith et al, 1993/. The assumption of random distribution of foliage in a canopy may be valid for many closed deciduous forests, pastures, grasslands, and agricultural crops, but it is inavlid for open-canopy forests: boreal coniferous and aspen forests /Chen et al, 1997; Kucharik et al, 1997/ and open-canopy temperate forests /Lang et al, 1985; Gholz et al, 1991; Gower and Newman, 1991; Fassnacht et al, 1994; Chen et al, 1997/. For a given LAI, radiation transmission is greater through a canopy with nonrandomly (i.e. clumped) than randomly distributed foliage. Assuming that a random distribution of foliage can produce errors in excess of 100% /Fassnacht et al, 1994/, the success of the indirect approach to estimating LAI is correlated to how accurately a simplified radiation model can mimic the true canopy architecture /Welles and Cohen, 1996/. The canopy gap-size distribution and the gap fraction describe the clumping of elements in the canopy. Gap size is the actual dimension of gaps between individual elements, ranging from a fraction of a centimetre to several meters in coniferous canopies /Kucharik, 1997; Kucharik et al, 1997/. Gap fraction is the percentage of background area viewed from above (ground or understory), below (sky and clouds), or within a canopy /Gower et al, 1999/. Both gap fraction and gap-size distribution depend on the angle from which the canopy is viewed. A element clumping index ($\Omega_e(\theta)$), can be derived from canopy gap-size data, that can be related to LAI /Chen, 1996; Chen and Cihlar, 1996; Chen et al, 1997; Kucharik et al, 1997/.

Several optical instruments that measure canopy gap fraction from beneath, or within, plant canopies, over a range of zenith angles are commercially available /Welles, 1990; Welles and Cohen, 1996/. However, measuring the canopy gap-size distribution is difficult; therefore a simplified approach for estimating $\Omega_e(\theta)$ has been proposed by /Kucharik et al, 1998/, where the ratio of the crown depth (base of live crown to top of canopy) to crown diameter (measured at the widest extent) can be used for calculating $\Omega_e(\theta)$ /Gower et al, 1999/.

/Gower et al, 1999/ compare direct and indirect estimates of LAI corrected for foliage clumping and woody tissue, for a variety of ecosystems. They note that indirect estimates of LAI plateau around 5–6, while direct estimate reach 9. Therefore, they conclude that direct measurements is the only reliable approach for canopies with a LAI > 6.

4.1.4 Conclusions

It can be concluded that the estimation of LAI of a vegetation canopy on the basis of optical remote sensing is not straightforward, although it is the only means of obtaining the spatial distribution of LAI /Liu et al, 1997/. Since several parameters affect the spectral reflectance from a vegetation canopy no unique relationship between LAI and a vegetation index can be expected to be applicable everywhere and et all times, even for a particular sensor. One of the most serious limitations is that the indices quickly saturate and become insensitive to variations of LAI for high LAI-values. Theoretical estimations show that LAI may be retrievable accurately and reliable only when the canopy is optically thin enough to allow a significant illumination of the underlying soil, and when the optical properties of this soil are such that the radiance field emerging from this level is sufficient different from that exhibited by a deeper canopy /Gobron et al, 1997/.

LAI estimation from satellite data requires ground data for validation and test for bias. There is also evident that vegetation properties and background significantly affect the relationships between vegetation indices and LAI /Turner et al, 1999/, suggesting that for obtaining local accuracy in derivation of LAI surfaces it will be desirable to stratify by land cover types (e.g. physiognomic type and successional stage) and to chose the optimal vegetation index for each stratum.

4.2 FPAR

FPAR, the fraction of PAR (photosynthetically active radiation) absorbed by the plant canopy, is an essential parameter relating the available visible solar radiation to its absorption by chlorophyll for plant photosynthesis. It is one of the surface parameters quantifying the CO_2 uptake by plants and release of water through evapotranspiration (http://www.wmo.ch/web/gcos/terre/variable/radfra.html).

The product of PAR surface irradiance and FPAR gives the amount of absorbed photosynthetically active radiation, APAR /Prince, 1991a/. Absorbed PAR (APAR) energy can be related to the photosynthetic activity of vegetation if it is integrated from sunset to sunrise /Baret and Guyot, 1991/. In such conditions the vegetation index to FPAR relation corresponds to the situation where radiometric data are measured at noon, with clear sky conditions, and compared to daily averaged FPAR.

4.2.1 The relationship with vegetation indices

The relationship between FPAR and top of the canopy spectral vegetation indices have been empirical shown in several investigations /Daughtry et al, 1983; Asrar et al, 1984; Hatfield et al, 1984; Gallo et al, 1985; Wiegand et al, 1991; 1992; Hall et al, 1992a,b; among others/. The relationship has also been demonstrated quasitheoretically using radiative transfer models of varying degree of detail /Sellers, 1985; Choudhury, 1987; Baret and Guyot, 1991; Asrar et al, 1992; Goward and Huemmrich, 1992; Myneni et al, 1992; among others/. The evaluation of FPAR requires integration of the spectral absorptance over the 0.4–0.7 µm wavelength interval /Myneni et al, 1992/. However, FPAR can be estimated to 95% of its true value by the waveband 0.589–0.685 µm /Myneni and Williams, 1994/. Thus, the fraction of radiation absorbed by the canopy at red wavelength is a good approximation of the fraction of total PAR absorbed.

The NDVI-FPAR relations are linear in most cases, with the exception of canopies with bright NDVI backgrounds (high understory LAI) /Myneni et al, 1997/. The relationship is independent of pixel heterogeneity (ground cover, plant leaf area, and variations in leaf orientation and optical properties) /Myneni and Williams, 1994/. On the other hand, the relationship is sensitive to background, atmospheric, and bidirectional effects. An increase in soil reflectance decreases TOC (top of the canopy) NDVI and increases FPAR. Because of the positive atmospheric effects at red wavelengths and negative atmospheric effect at near-infrared TOA (top of the atmosphere) NDVI is less than TOC NDVI. If off-nadir observations of NDVI are used (e.g. off-nadir AVHRR data) bidirectional effects due to surface reflectance anisotropy play a large role in the remote sensing of FPAR /Myneni and Williams, 1994/. With an increase in leaf area, off-nadir canopy reflectance at near-infrared increases while red reflectance decreases. As a result, TOC NDVI increases with zenith angle in the principal plane, except for the minimum encountered about the retrosolar direction due to the hot spot effect which increases red reflectances substantially.

/Myneni and Williams, 1994/ propose a simple linear model for relating FPAR to TOC NDVI:

$$FPAR = 1.164 \cdot TOC\ NDVI - 0.143\ (r^2 = 0.919, samples = 252)$$

In /Myneni et al, 1995a/ the same relationship is slightly modified:

$$FPAR = 0.8465 \cdot TOC\ NDVI - 0.1083\ (r^2 = 0.943, samples = 280)$$

The model is valid for: a) solar zenith angle less than 60°; b) view zenith angles about the nadir or less than 30°c) soils or backgrounds of moderate brightness (NDVI about 0.12); d) atmospheric optical depths less than 0.65 at 0.55 µm.

When using satellite data, atmospheric and bidirectional effects must be corrected, and background contributions to the signal must be accounted for.

4.2.2 The relationship with LAI

The relationship between FPAR and LAI is near-linear at LAIs < 3, after which it tends to an asymptotic value of 0.95 depending on the canopy, soil, and atmospheric parameters /Myneni and Williams, 1994/.

FPAR is often expressed as a function of LAI. Field measurements performed on different crops such as wheat /Hipps et al, 1983/, maize /Gallo et al, 1985/, cotton /Wiegand and Richardsson, 1990/, and grassland /Weiser et al, 1986/ show that the seasonal behaviour of

FPAR, as a function of LAI, can be expressed by an exponential function based on Beer's law /Baret and Guyot, 1991/:

$$FPAR = FPAR_{\infty}[1 - B \cdot \exp(- K_p \cdot LAI)]$$

Where $FPAR_{\infty}$ is the asymptotically limiting value of PAR absorption for infinite thick canopy ($FPAR_{\infty} \approx 0.94$) /Wiegand and Hatfield, 1988/, see also above (0.95 according to /Myneni and Williams, 1994/). *B* is a parameter ranging between 0.8 and 1.2, depending on experimental errors and deviation from model assumption (random distribution of leaves) (*B* is usually set to 1). K_p is a coefficient which controls the slope of the relationship (equivalent to an extinction coefficient).

4.2.3 Ground measurements

The direct measurements of APAR in the field can be challenging, especially in heterogeneous canopies such as forests. Usually FPAR is measured directly with a method that spatially averages: then continuous measurements of PAR are used to get long-term APAR estimates. /Gower et al, 1999/ recommend instantaneous measurements of FPAR to be done under overcast conditions to obtain the most consistent values of APAR.

FPAR is calculated as follows /Gower et al, 1999/:

$$FPAR = [(PAR_{\downarrow AC} - PAR_{\uparrow AC}) - (PAR_{\downarrow BC} - PAR_{\uparrow BC})]/ PAR_{\downarrow AC}$$

Where $PAR_{\downarrow AC}$ and $PAR_{\uparrow AC}$ are incident (downward) and reflected (upward) PAR above the canopy, respectively, and $PAR_{\downarrow BC}$ and $PAR_{\uparrow BC}$ are the corresponding terms for below the canopy. The equation can also be solved for the fraction of incident to reflected PAR for above (ρ_{AC}) and below (ρ_{BC}) the canopy /Gower et al, 1999/:

$$FPAR = [1-\rho_{AC}(t)] - [1-\rho_{BC}(t)] (PAR_{\downarrow BC/} PAR_{\downarrow AC}).$$

The term $PAR_{\downarrow BC/} PAR_{\downarrow AC} = 1-$ FIPAR, where FIPAR is the fraction of PAR intercepted by the canopy. Many studies of light interception in canopies use FIPAR instead of FPAR because it is easier to measure and almost the same value. Typically FIPAR is within 4% of FPAR /Gallo and Dughtry, 1986; Russel et al, 1989; Gower et al, 1999/. However, if LAI is very low (≈ 0.2) and the soil is very reflective (PAR reflectance = 0.5), then FPAR may be 40% larger than FIPAR for a random canopy because additional PAR reflected from the soil is absorbed by the leaves.

An alternative way of calculating FPAR used in the BEPS model to calculate primary production of Canada is given in /Liu et al, 1997/. The calculation is based on coefficients from /Chen, 1996/ and the solar zenith angle at noon.

Unlike LAI FPAR exhibits diurnal variation. Its use in models with time steps longer than a day requires appropriate time integration /Myneni et al, 1997/.

4.2.4 Measurements of PAR

Incident PAR can be measured directly or inferred from insolation measurements. Under clear skies, the ratio of PAR and insolation varies little around 0.48, except at high solar zenith angles or extreme water vapor amounts /Frouin and Pinker, 1995/. The effect of aerosols is only significant when horizontal visibility is less than 10 km. Under cloudy skies, however, cloud optical thickness substantially changes the ratio of PAR-to-insolation, which can vary by more than 50% at low sun zenith angles.

Several attempts have been made to estimate insolation from satellite data /Tarpley, 1979; Gautier et al, 1980; Möser and Raschke, 1984; Pinker and Ewing, 1985; Dedieu et al, 1987; Darnell et al, 1988; among others/, as well as PAR directly /Frouin and Gatier, 1990; Eck and Dye, 1991; Pinker and Laszlo, 1992; Frouin and Pinker, 1995/. /Frouin and Pinker, 1995/ conclude in their review of current satellite algorithms to estimate PAR that accuracies better than 10% for PAR estimates appear feasible on a monthly time scale. For primary productivity estimates this is acceptable since the-state-of-the-art models of primary productivity involve terms other than PAR that are more difficult to estimate.

4.3 Primary production

Net primary production (NPP), the annual net production of biomass, comprises roughly 50% of net canopy photosynthesis /Landsberg and Gower, 1997/, and is an important component of net ecosystem exchange. The conceptual definition of NPP is widely accepted /Field et al, 1995; Gower et al, 1999/:

$NPP = GPP – R_{A,}$

Where GPP (gross primary production) is the carbon fixed during photosynthesis, and R_A is autotrophic respiration. However, GPP cannot be measured directly, and R_A is difficult to measure, especially in large stature or multi-species forests. Alternatively, NPP, can be estimated according to /Gower et al, 1999/:

$NPP = \sum P_i + H,$

where *P* is the net production of dry biomass for each of the plant tissues (i), (all plant tissues should be included: wood, foliage, reproductive tissue, and roots including mycorrhizae), and H is consumption of organic matter by herbivores. Thus, NPP is the sum of above-ground net primary production (ANPP), and below-ground net primary production (BNPP). Despite the fact that BNPP equals or exceeds ANPP for many ecosystems, estimates of BNPP are rare compared to ANPP estimates /Landsberg and Gower, 1997; Gower et al, 1999/. The reason for this is that estimating BNPP is both difficult and controversial /Lauenroth et al, 1986; Vogt et al, 1986a,b; Nadelhoffer and Raich, 1992; Publicover and Vogt, 1993; Steele et al, 1997/. Two common approaches to estimating ANPP are area harvest and allometry (see section 4.1.3.). A review of different methods to estimate BNPP is given in /Gower et al, 1999/.

Process models, driven by remotely sensed data, are useful tools for estimating NPP for larger areas than can be quantified using field-based measurements. However, an incomplete understanding of the influence of abiotic and biotic factors on carbon allocation limits further development of process models. /Gower et al, 1999/ observe that for the immediate future, scientists will be using average carbon allocation coefficients for major biomes, and adjusting these ratios based on simple indices of water and nutrient availability /sensu Running and Gower, 1991/. This approach requires average and maximum and minimum below-ground to total NPP ratios for major biomes (a compilation of such ratios is given in /Gower et al, 1999/).

The potential of using satellite data to estimate primary production has been investigated in several studies. /Tucker at al, 1985/ found that seasonal sums of NDVI were correlated with the seasonal primary production. A number of following studies based on field measurements of production /Prince and Tucker, 1986; Diallo et al, 1991; Prince, 1991b; Wylie et al, 1991/ and on estimates of biome production /Goward et al, 1985, 1987/ confirmed these findings and encouraged the view that satellite data, such as the NOAA AVHRR data, can be used to monitor global primary production /Tucker et al, 1986; NASA, 1987; Becker et al, 1988/. However, a weakness in these relationships, are that they depend on analogies with models on crop production and not on models specially designed to take account of the degree of variation to be expected at the regional and global scales /Prince, 1991a/. Whereas crop models can take advantage of simplified assumptions, such as constant respiration/net production ratios, these models are unlikely to apply to typical vegetation cover at a regional or global scale, consisting of plants having different types of growth physiology.

/Warren Wilson, 1967/ and /Monteith, 1972, 1977/ suggested a form of primary production model for crops that attributes variation in primary production to differences in the amount of PAR absorbed by the plant canopy (APAR). /Kumar and Monteith, 1981/ and others /e.g. Asrar et al, 1984; Hatfield et al, 1984; Gallo et al, 1985; Sellers, 1985, 1989/ further noted that vegetation index such as NDVI and the SR are approximately linearly related to the percentage PAR absorbed by the canopy (FPAR) (see section 4.2). These two relationships can be combined /Kumar and Monteith, 1981; Steven et al, 1983/ to create a model in which primary production is related to temporal sums of NDVI by means of the dry-matter yield of energy, ε /Prince, 1991a/:

$$P = \varepsilon \sum_{t} (NDVI_t S_t)$$

where P is the seasonal production (kg/ha), $NDVI_t$ is the normalised difference index measured at the surface of the vegetation during time interval *t*, and S_t is the global PAR incident during time interval *t*.

The value of ε is affected by aspects of the physical environment, such as temperature /Jarvis and Leverenz, 1983; Squire et al, 1984a,b; Mohammed et al, 1988/, soils /Allen and Scott, 1980/, water /Green et al, 1985; Linder, 1985; Byrne et al, 1986/, nutrition /Green, 1987; Steven and Demetriades-Shah, 1987/, and ontogenetic changes that occur throughout the life cycle of a plant /Jarvis and Leverenz, 1983/. Although ε is not a constant it seems to occupy quite a narrow range /Kiniry et al, 1989; Russel et al, 1989; Prince, 1991a/. A compilation of field measurements of ε for some herbaceous crops and certain other types of vegetation given in /Prince, 1991a/ shows that experimental values of ε lie between 0.2 and 4.8 gMJ^{-1} compared with theoretical maxima in the range 4.5–7.6 gMJ^{-1}. /Prince, 1991a/ also conclude that although in the short term there is many factors that affect ε, the seasonal mean ε is less subject to change and might be regarded as constant for an entire growing season /Kumar and Monteith, 1981; Steven et al, 1983; NASA, 1987/.

The proportionality between NPP and absorbed photosynthetically active radiation has become known as the light use efficiency or epsilon (ε) model. Light use efficiency (LUE) models are widely used today to simulate NPP for terrestrial biomes /Heimann and Keeling, 1989; Potter et al, 1993; Running and Hunt, 1993; Ruimy et al, 1994; Field et al, 1995; Prince and Goward, 1995; Hunt et al, 1996; Liu et al, 1997/. The basis for the model is that photosynthetic fixation of carbon by leaves is proportional to absorbed visible quanta /McCree, 1972/, and, it is nearly linear for most canopies /Hesketh and Baker, 1967/.

The LUE model has two advantages /Gower et al, 1999/: 1) The model is simple, and some evidence exists to suggest that maximum light use efficiency may be conservative within major vegetation classes, and 2) the fraction of photosynthetically active radiation absorbed by green leaves in a canopy (FPAR) can be remotely sensed, as has been showed in both empirical /e.g. Daughtry et al, 1983; Steinmetz et al, 1990; Landsberg et al, 1997/ and theoretical studies /Kumar and Monteith, 1981; Myneni et al, 1995a,b/.

The CASA (Carnegie-Ames-Stanford Approach) model for example, introduced by /Potter et al, 1993/ and expanded by /Field et al, 1995/, is structured so, that for a given area the amount of PAR absorbed annually by green vegetation (APAR) multiplied by the efficiency by which that radiation is converted to plant biomass increment (ε) equals the net primary production (NPP). The model is based on ε, but with a structure that allows ε to vary seasonally and within biomes, and without recourse to ecosystem-specific ε values. APAR is calculated at each monthly time-step as the product of PAR surface irradiance and FPAR. PAR surface irradiance is calculated as half the total solar surface irradiance from the data of /Bishop and Rossow, 1991/. FPAR is derived from AVHRR NDVI. CASA calculates ε for each grid cell as the product of a globally uniform maximum ε*, determined using a calibration with field data, and scalar representing the availability of water (W) and the suitability of temperature (T_1, T_2). NPP for a location (*x*) and time (*t*) is represented as /Field et al, 1995/:

$$NPP(x,t) = APAR(x,t) \cdot \varepsilon(x,t),$$

or as

$$NPP = S(x,t) \cdot FPAR(x,t) \cdot \varepsilon^* \cdot T_1(x,t) \cdot T_2(x,t) \cdot W(x,t)$$

Where S is the solar surface irradiance.

/Field et al, 1995/ give a compilation of ε used in the CASA model compared to ε used by /Ruimy et al, 1994/ and ε that have been inferred from /Lieth, 1975/. The model of /Ruimy et al, 1994/ uses different ε for different ecosystems based on a comprehensive review of the literature.

A more complex model to estimate ecosystem productivity is the boreal ecosystems productivity simulator (BEPS) developed at the Canada Centre for Remote Sensing /Liu et al, 1997/. The model uses principles of the process model, FOREST-BGC developed by /Running and Coughlan, 1988/ for site-level, later extended to simulate ecological and hydrological processes at the landscape scale /Running et al, 1989/. BEPS integrates and uses processed remote sensing data of LAI and land-cover type, daily meteorological data including air temperature, incoming shortwave radiation, precipitaion, and humidity, and soil-data (available water-holding capacity). The major outputs of BEPS are spatial field (1 km resolution) of net primary productivity (NPP) and evapotranspiration.

5 Available products

There is a new moderate-resolution sensor, MODIS (Moderate Resolution Imaging Spectroradiometer), designed to improve the understanding of global dynamics and processes occurring on land, in the oceans, and in the lower atmosphere, that will provide users with a series of interesting products.

MODIS is a key instrument aboard the Terra (EOS AM) and Aqua (EOS PM) satellites. Terra's orbit around the Earth is timed so that it passes from north to south across the equator in the morning, while Aqua passes south to north over the equator in the afternoon. Terra MODIS and Aqua MODIS are viewing the entire Earth's surface every 1 to 2 days, acquiring data in 36 spectral bands, or groups of wavelengths.

LAI and FPAR products with global coverage are available from the MODIS sensor. The products are based on 8 days composites and are available with 1 km resolution The LAI product will be a LAI value between 0 and 8, the FPAR a value between 0.0 and 1.0. The products are still experimental in nature upon their initial release. Investigations are underway to assess the scientific validity of these products.

Other products of interest are for example MODIS Vegetation Indices (NDVI and a new Enhanced Vegetation Index (EVI)) available with 250 m resolution, MODIS Net Photosynthesis, based on 8-day composites (1 km resolution), and MODIS Net Primary Production (yearly estimates, 1 km resolution). All products are for the moment free of charge. Table 5-1 gives an overview of some available and planned MODIS-products of interest.

Table 5-1. Some of the available and planned MODIS products of interest (February 2003)(http://edcdaac.usgs.gov/modis/dataprod.html).

Product	Terra V001 ISIN – Beta Deleted January 31, 2003	Terra V003 ISIN – Provisional	Terra V004 SIN – Validated	Aqua V003 SIN – Provisional
Surface Reflectance				
MODIS Surface Reflectance 8-Day L3 Global 500 m	MOD09A1	MOD09A1	MOD09A1	MYD09A1
MODIS Surface Reflectance Daily L2G Global 500 m	MOD09GHK	MOD09GHK	MOD09GHK	MYD09GHK
MODIS Surface Reflectance Daily L2G Global 250 m	–	MOD09GQK	MOD09GQK	MYD09GQK
MODIS Surface Reflectance Quality Daily L2G Global 1 km	MOD09GST	MOD09GST	MOD09GST	MYD09GST
MODIS Surface Reflectance 8-Day L3 Global 250 m	–	MOD09Q1	MOD09Q1	MYD09Q1
Vegetation Indices				
MODIS Vegetation Indices 16-Day L3 Global 500 m	MOD13A1	MOD13A1	MOD13A1	MYD13A1
MODIS Vegetation Indices 16-Day L3 Global 1 km	MOD13A2	MOD13A2	MOD13A2	MYD13A2
MODIS Vegetation Indices 16-Day L3 Global 250 m	–	MOD13Q1	MOD13Q1	MYD13Q1
Leaf Area Index/Fraction of Photosynthetically Active Radiation (LAI/FPAR)				
MODIS Leaf Area Index/FPAR 8-Day L4 Global 1 km	MOD15A2	MOD15A2	MOD15A2	MYD15A2
Net Primary Vegetation Production				
MODIS Net Photosynthesis 8-Day L4 Global 1 km	MOD17A2	MOD17A2	MOD17A2	MYD17A2
MODIS Net Primary Production Yearly L4 Global 1 km	–	–	MOD17A3	MYD17A3
MODIS Evapotranspiration/Surface Resistance 8-Day L4 Global 1 km	–	–	–	MYD16A2

6 Production of NDVI-images for Forsmark and Oskarshamn

6.1 Introduction

Parallel to the literature review NDVI-images were also produced for the Forsmark and Oskarshamn investigation areas as a first step for future analysis. The NDVI-images were derived from the same satellite images that were used for production of the vegetation databases over the areas /Boresjö Bronge and Wester, 2003/. Unfortunately, it was not possible to obtain calibration information for the SPOT images used, so calibration of data into radiance or reflectance before analysis could not be performed. This means that the NDVI-images produced cannot directly be compared, only used for relative analysis within the images.

6.2 Forsmark

Two results have been produced for Forsmark, one based on the older Landsat5 TM-data from 1989-07-07, the other based on the SPOT4-image from 1999-08-01. The TM-data was calibrated into at-satellite reflectance before analysis according to /Markham and Barker, 1986/. The SPOT-data was analysed without calibration since calibration information could not be obtained. The NDVI results produced from SPOT-data was stratified according to vegetation type and structure.

NDVI was calculated according to the following:

Landsat TM	(TM4 – TM3)/(TM4 + TM3)
SPOT	(XI3 – XI2)/(XI3 + XI2)

This gives values ranging from –1 to 1. To convert the results into positive values (8 bits integer) ranging from 0 to 254 the following formula was applied:

$$NDVI_{INT} = (NDVI + 1) \cdot 127$$

6.2.1 Stratification of the SPOT NDVI-result

As been concluded previously the relationship between vegetation indices and LAI is not straightforward. Vegetation properties (e.g. physiognomic type and succesional stage) and background significantly affect the spectral reflectance from a vegetation canopy and no unique relationship can be expected between LAI and a vegetation index. Therefore, NDVI-values generated for an area with complex vegetation cover, are not directly comparable in the sense of expressing amount of green biomass.

To reduce this problem to some extent, and also to prepare for future calibration with ground data, the SPOT NDVI-image for Forsmark was roughly stratified with regard to vegetation type and structure to produce layers were the NDVI-values can be considered to be fairly comparable. The following layers were created based on the vegetation database (Table 6-1):

- No green biomass – no NDVI-values are shown (coastal bare rocks, built-up areas, other hard surfaces, and water).
- No tree layer or tree layer with crown coverage < 30% (clear-cut areas, open wetlands, arable land and pastures). A random distribution of biomass is assumed (see pages 17 and 20).
- Sparse tree layer, 30–60% crown coverage (dry pine forest on acid rocks). Clumped distribution of biomass, structure, bright background.
- Dense tree layer, > 60% crown coverage. Older coniferous forests (spruce, pine, mixed forest, forested wetlands with spruce or pine). Clumped distribution of biomass, structure, successional stage. Further division between spruce and pine is possible if necessary.
- Dense tree layer, > 60% crown coverage. Younger coniferous forests on clear-cut areas (spruce, pine, undefined coniferous, mixed forest/shrubs on bedrock islands). Clumped distribution of biomass, structure, successional stage.
- Dense tree layer, > 60% crown coverage (deciduous forest). Random distribution of biomass, structure, bright field layer.

Table 6-1. Stratification of the SPOT NDVI-image into layers according to vegetation and structure based on the vegetation database /Boresjö Bronge and Wester, 2003/.

Produced layer (Appendix 1)	Code in the vegetation database (vegetation/land cover classification)
No green biomass	Coastal bare rocks (83), built-up areas (91–93), other hard surfaces (96), water (100).
Tree layer < 30% crown coverage	Clear-cut areas (45, 46, 50, 64), open wetlands (72, 74–75, 77–79), arable land (81), meadow/pastures (82).
Sparse tree layer, 30–60% crown coverage	Dry pine forest on acid rocks (15).
Dense tree layer, > 60% crown coverage, older conifers	Spruce-dominated (11, 12), pine-dominated (13, 14), mixed forest (31), forested wetland with spruce (61), forested wetland with pine (62).
Dense tree layer, > 60% crown coverage, younger conifers	Clear-cut with spruce (41), clear-cut with pine (42), clear-cut with undefined conifers (43), mixed forest/shrubs on bedrock islands.
Dense tree layer, > 60% crown coverage, deciduous	Deciduous forest (21, 23, 26), forested wetlands with deciduous (63), open lush wetland with willow and birch (76)

6.2.2 Produced NDVI-images

Figure 6-1 shows the mask image used to stratifiy the NDVI result of Forsmark. Figures 6-2 to 6-6 show the five NDVI images produced by stratification according to Table 6-1. Figure 6-7 shows the unstratified NDVI-image produced based on Landsat TM-data from 1989-07-07.

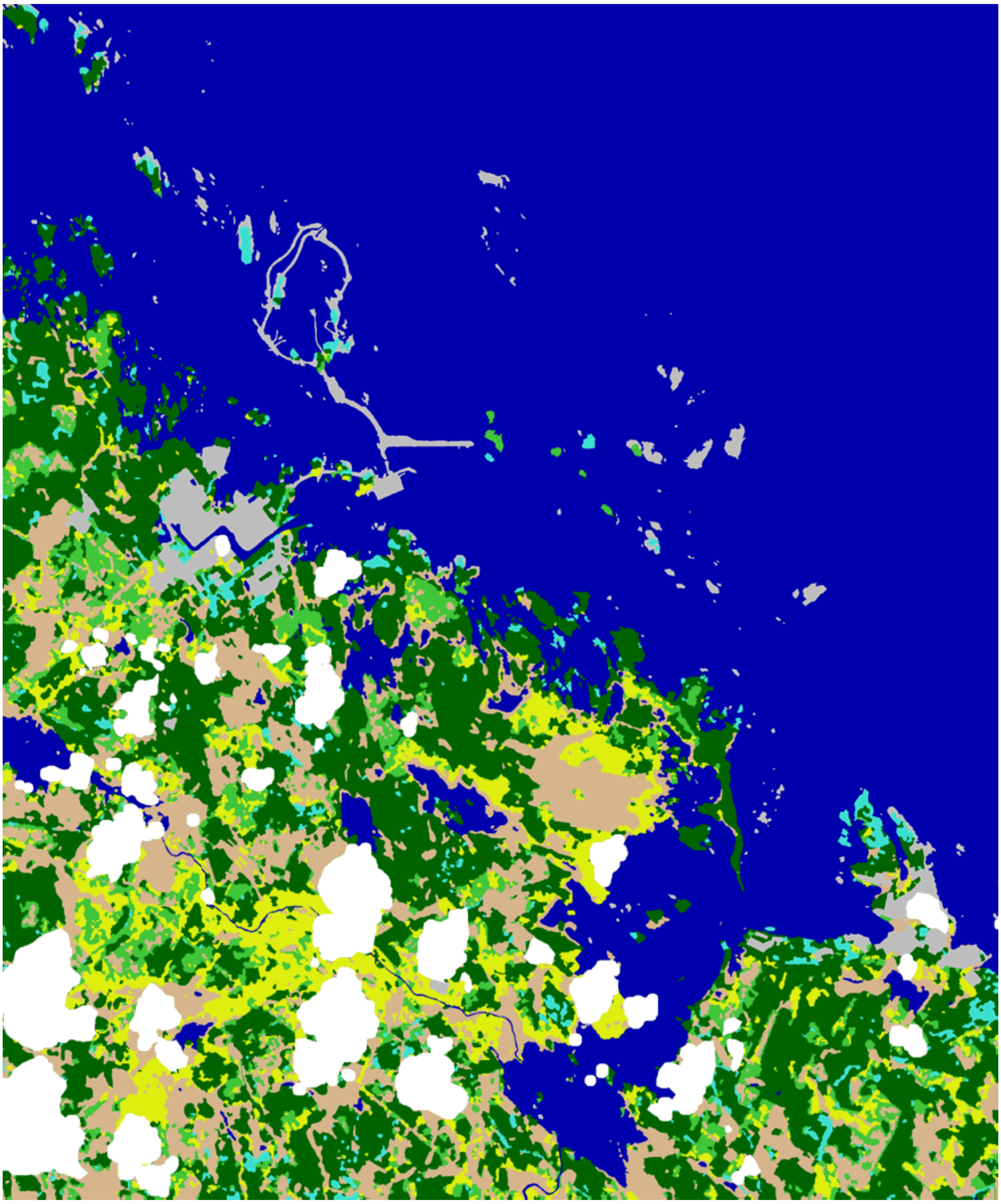

Figure 6-1. *Image used for stratification of the NDVI result over Forsmark (see Table 6-1). Grey = no green biomass. Beige = tree layer < 30% crown coverage. Aquamarine = tree layer 30–60% crown coverage, pine forest. Greenish-yellow = dense forest, deciduous (> 60% crown coverage). Dark green = dense forest, conifers (> 60% crown coverage). Light green = dense forest, younger conifers (> 60% crown coverage). Blue = water. White = cloud or cloud shadow.*

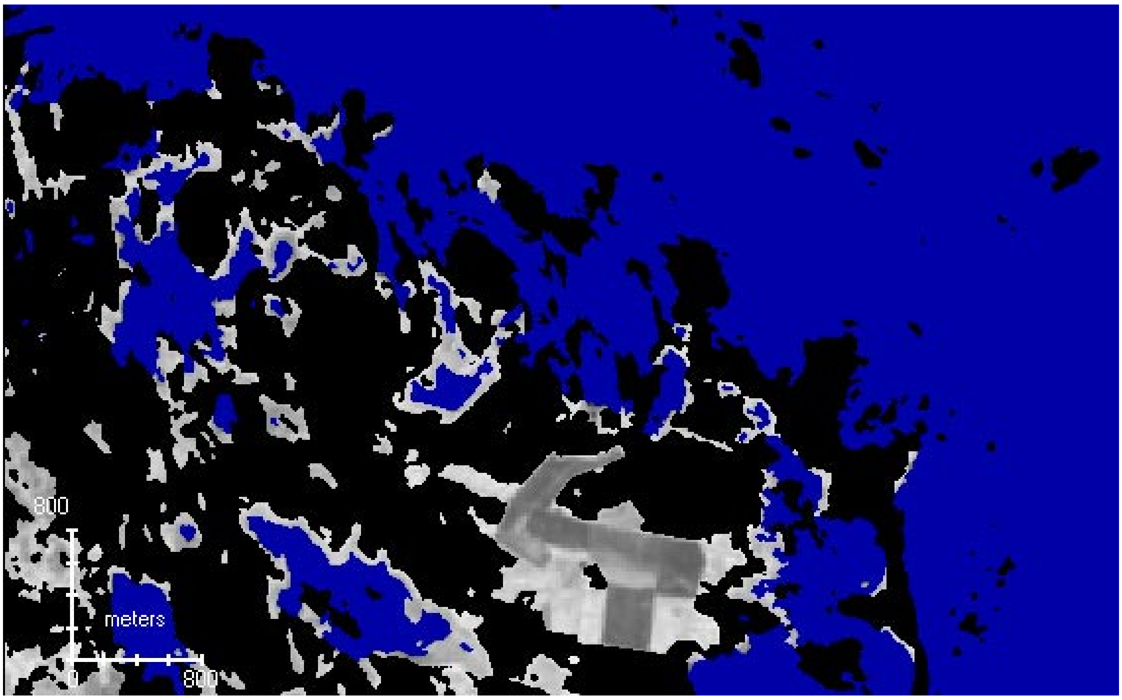

Figure 6-2. *NDVI-values (grey scale) for areas with a tree layer < 30% crown coverage for a part of Forsmark investigation area based on SPOT4-data from 1999-08-01. Blue = water. ark grey – light grey = increasing NDVI-values.*

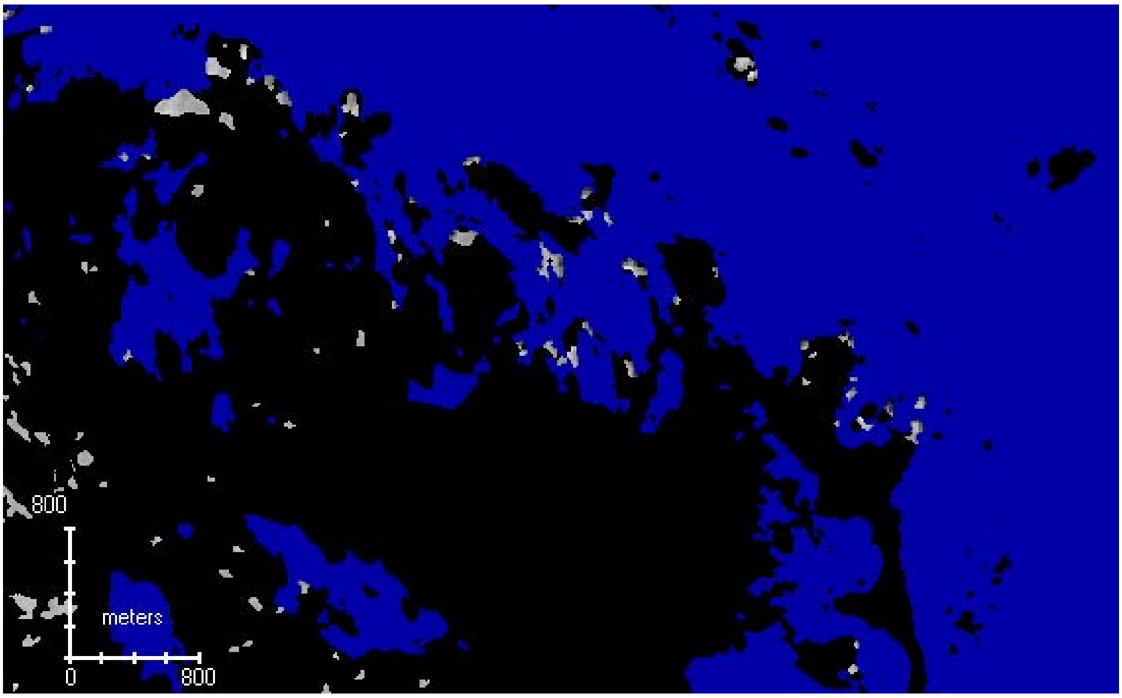

Figure 6-3. *NDVI-values (grey scale) for pine forest with tree layer 30–60% crown coverage for a part of Forsmark investigation area based on SPOT4-data from 1999-08-01. Blue = water. Dark grey – light grey = increasing NDVI-values.*

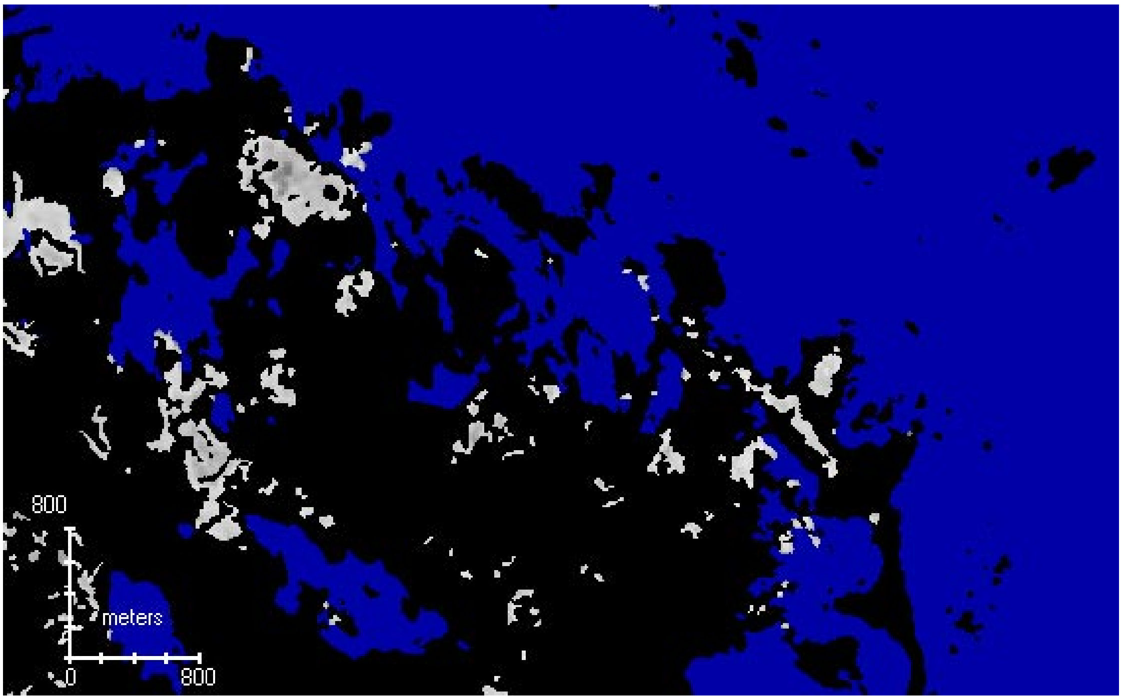

Figure 6-4. *NDVI-values (grey scale) for young coniferous forest (tree layer > 60% crown coverage) for a part of Forsmark investigation area based on SPOT4-data from 1999-08-01. Blue = water. Dark grey – light grey = increasing NDVI-values.*

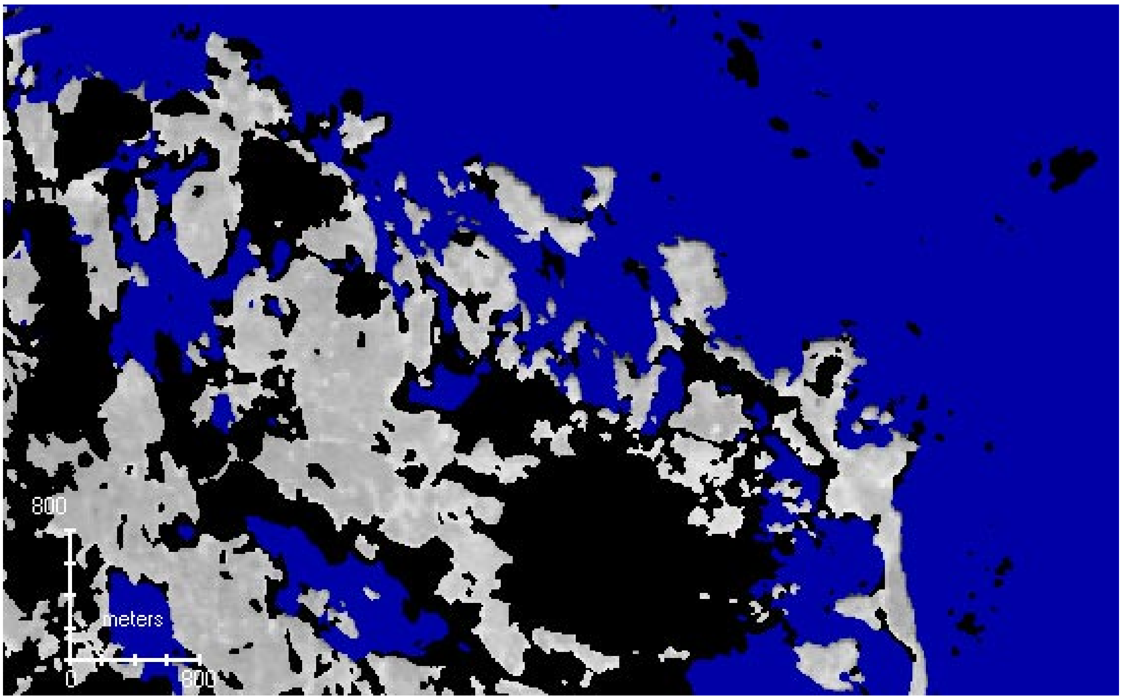

Figure 6-5. *NDVI-values (grey scale) for old coniferous forest (tree layer 30–60% crown coverage) for a part of Forsmark investigation area based on SPOT4-data from 1999-08-01. Blue = water. Dark grey – light grey = increasing NDVI-values.*

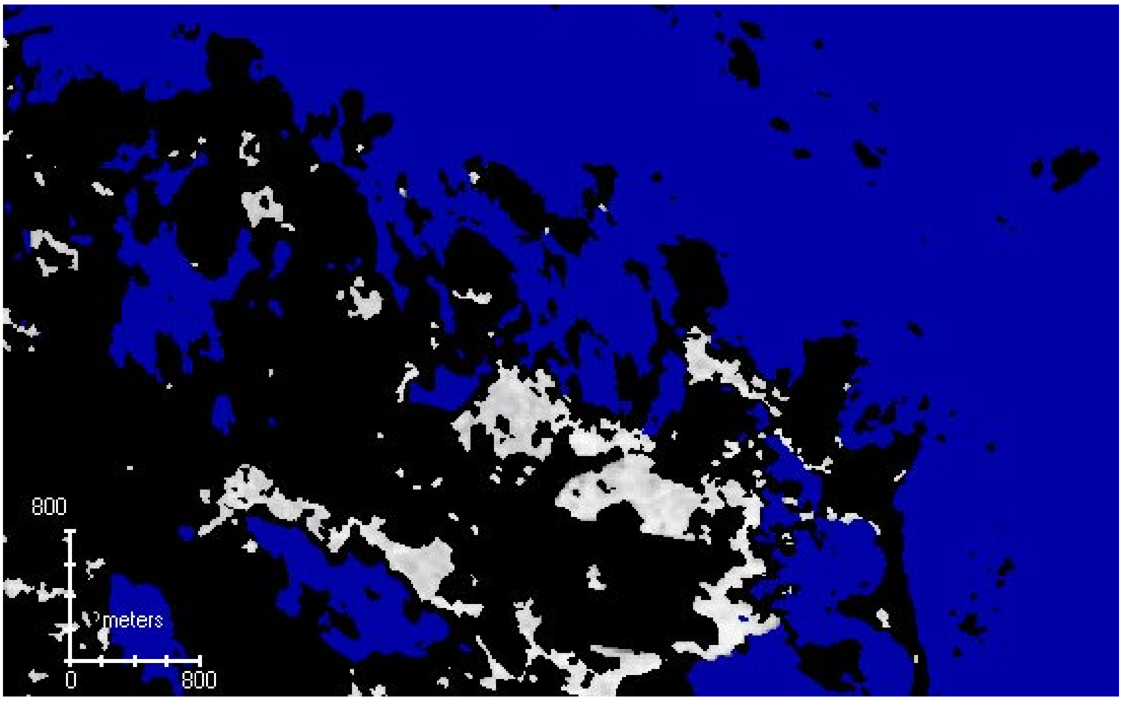

Figure 6-6. *NDVI-values (grey scale) for deciduous forest (tree layer 30–60% crown coverage) for a part of Forsmark investigation area based on SPOT4-data from 1999-08-01. Blue = water. Dark grey – light grey = increasing NDVI-values.*

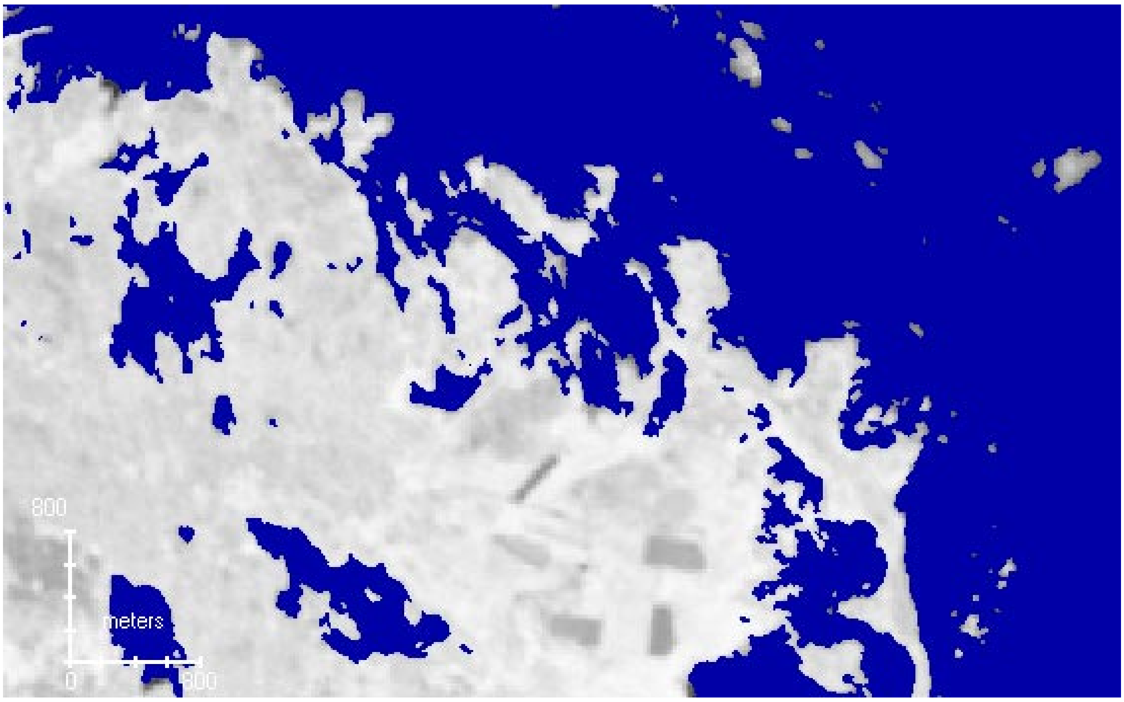

Figure 6-7. *NDVI-values (grey scale) for a part of Forsmark investigation area based on Landsat TM-data from 1989-07-07. No stratification has been made. Blue = water. Dark grey – light grey = increasing NDVI-values.*

6.3 Oskarshamn

One NDVI-image was produced for the area based on the SPOT-image from 1999-07-11 (Figure 6-8).

NDVI was calculated according to the following:

SPOT (XI3 – XI2)/(XI3 + XI2)

This gives values ranging from –1 to 1. To convert the results into positive values (8 bits integer) ranging from 0 to 254 the following formula was applied:

$NDVI_{INT} = (NDVI + 1) \cdot 127$

The SPOT-data was analysed without calibration since calibration information could not be obtained. No stratification was made, but can be performed with support of the vegetation database, if further analysis of the area will be made in the future.

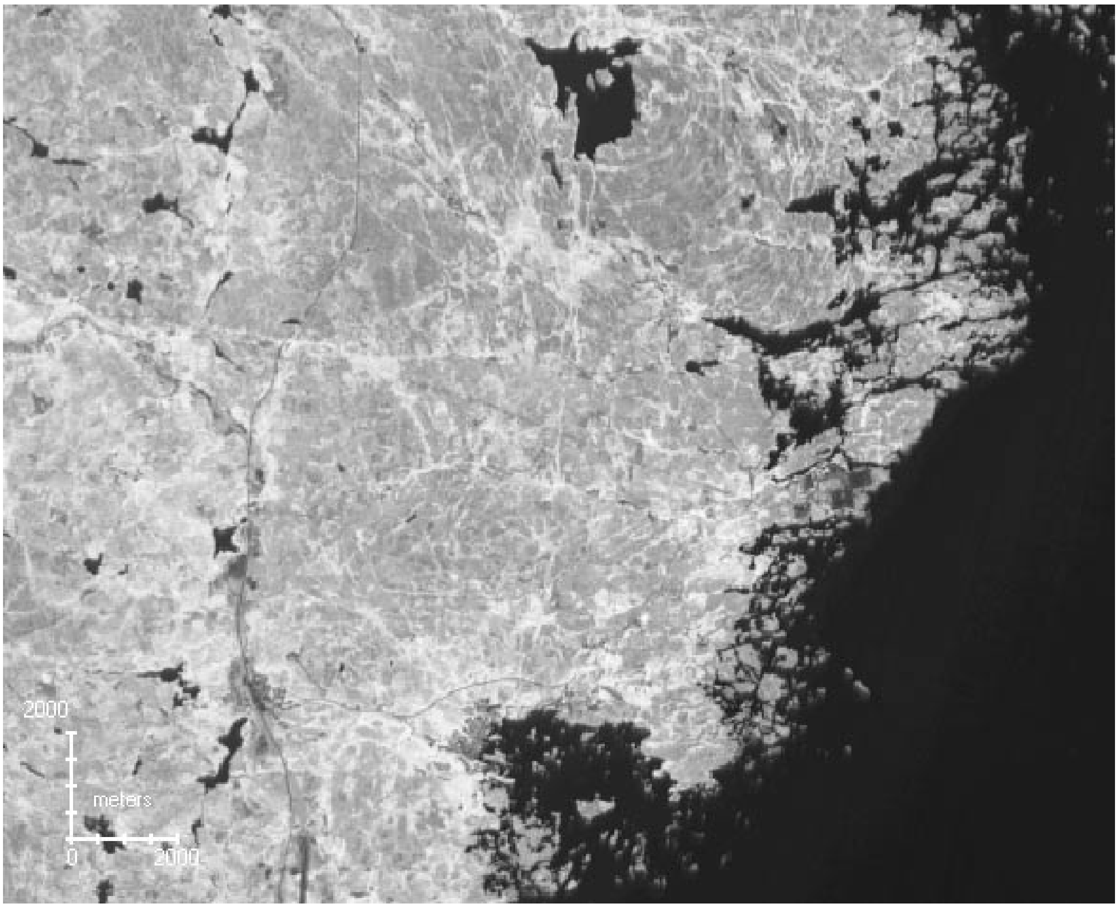

Figure 6-8. *NDVI-values over Oskarshamn investigation area based on the SPOT-image from 1999-07-11. No stratification has been made.*

7 Conclusions and recommendations

In the following the most essential information concerning satellite remote sensing for estimation of LAI, FPAR, and NPP are summarised, and recommendations are given on possible approaches for derivation of this information in the Forsmark and Oskarshamn areas.

7.1 Vegetation indices

Most vegetation indices combine information contained in two spectral bands: red and near-infrared. These indices are established in order to minimise the effect of external factors on spectral data and to derive canopy characteristics such as leaf area index (LAI) and fraction of absorbed photosynthetic active radiation (FPAR) /Baret and Guyot, 1991/.

The most commonly used indices to derive LAI and other surface parameters from space-borne and airborne remote sensing data are the simple ratio (SR) /Jordan, 1969/ and the normalised difference vegetation index (NDVI) /Rouse et al, 1974/.

SR and NDVI enhance the contrast between soil and vegetation and minimise the effects of illumination conditions, but they are sensitive to optical properties of soil background /Elvidge and Lyon, 1985; Huete et al, 1985/. Several indices therefore have been proposed to minimise the effects of soil background, e.g. the perpendicular vegetation index (PVI) / Richardson and Wiegand, 1977/, the weighted difference vegetation index (WDVI) /Clevers, 1986, 1989/, the soil adjusted vegetation index (SAVI) /Huete, 1988/, and the transformed soil adjusted vegetation index (TSAVI) /Baret et al, 1989/.

The strong differences in the sensitivity of spectral vegetation indices over different LAI ranges, vegetation types, and vegetation structures suggest that the optimal vegetation index for establishing an empirical relationship between LAI and vegetation index may differ depending on these factors /Turner et al, 1999/.

7.2 LAI

A large number of relationships have been established between vegetation indices and LAI. However, the estimation of LAI of a vegetation canopy on the basis of optical remote sensing is not straightforward, although it is the only means of obtaining the spatial distribution of LAI. Since several parameters affect the spectral reflectance from a vegetation canopy no unique relationship between LAI and a vegetation index can be expected to be applicable everywhere and all the time, even for a particular sensor. One of the most serious limitations is that the indices quickly saturate and become insensitive to variations of LAI for high LAI-values.

LAI estimation from satellite data requires ground data for validation and test for bias. There is also evident that vegetation properties and background significantly affect the relationships between vegetation indices and LAI /Turner et al, 1999/, suggesting that for obtaining local accuracy in derivation of LAI surfaces it will be desirable to stratify by land-cover types (e.g. physiognomic type and successional stage) and to use the optimal vegetation index for each stratum.

7.2.1 Recommendation for continued work

Two main approaches to estimate LAI from remote sensing data are distinguished, use of advanced models based on radiative transfer theory and use of empirically established relationships. Both approaches need ground truth for calibration.

A possible approach for satellite-data based estimation of LAI in Forsmark and Oskarshamn include:

- Establishing empirical relationships between satellite-data derived vegetation indices and LAI for site-specific vegetation types. The produced vegetation database /Boresjö Bronge and Wester, 2003/ is used for stratification of the area into structural types that can be assumed to display different relationships between vegetation indices and LAI. The most optimal vegetation index is selected for each stratum for production of LAI for the whole area. Calibration of satellite data into reflectance is recommended before analysis so that comparable results are produced.
- The approach also involves direct or indirect estimation of LAI on ground, or use of available established relationships applicable to Swedish conditions, and use of atmospherically corrected satellite data. It is also possible to use measuring instruments such as the Lai-2000 plant canopy analyzer (Li-Cor, Inc, Lincoln, NE) in estimating leaf area index from ground /Stenberg et al, 1994/. However, correction for shading of the needles on the shoots has to be done.

The produced LAI-database can be used to test the local validity of the available MODIS-product LAI (1 km resolution). If the MODIS LAI data give a reasonable estimate of LAI for the area for a comparable period of time, this data could be an alternative for continued monitoring of the parameter in the test areas. Alternatively the 250 m reflectance data from MODIS can be used for local derivation of LAI based on the empirical relationship established. The advantage with this approach, if reliable, is that these data can be obtained daily or as 8-days composite products.

7.2.2 Data requirements

Satellite data

- SPOT or Landsat TM-data from one or two recording dates during July or August. (Two images will give an indication of the variations in the results that are due to scene/phenological variations).
- MODIS LAI data and 250 m reflectance data (daily and 8-days products) for the same time periods for test of their usefulness for future monitoring. MODIS-data are at present free of charge.

Other data

- Estimation of LAI on ground (area harvest or application of allometric equations to stand diameter).

7.3 FPAR

The relationship between FPAR and top of the canopy spectral vegetation indices have been empirical and theoretically shown in several investigations. The NDVI-FPAR relations are linear in most cases, with the exception of canopies with bright NDVI backgrounds. The relationship is independent of pixel heterogeneity (ground cover, plant leaf area, and variations in leaf orientation and optical properties). On the other hand, the relationship is sensitive to background, atmospheric, and bidirectional effects. A simple linear model for relating FPAR to top of the canopy NDVI have been proposed by /Myneni and Williams, 1994/. The model is valid for solar zenith angle less than 60°; view zenith angles about the nadir or less than 30°, soils or backgrounds of moderate brightness (NDVI about 0.12); and atmospheric optical depths less than 0.65 at 0.55 μm.

The product of PAR surface irradiance and FPAR gives the amount of absorbed photosynthetically active radiation, APAR /Prince, 1991a/. Absorbed PAR (APAR) energy can be related to the photosynthetic activity of vegetation if it is integrated from sunset to sunrise /Baret and Guyot, 1991/.

7.3.1 Recommendation for continued work

A possible approach for derivation of FPAR for calculation of APAR include:

- Apply the relationship proposed by /Myneni and Williams, 1994/ for derivation of FPAR from satellite-data derived NDVI. The relationship is valid for top of the canopy NDVI, so satellite data must be atmospherically corrected. Validation against independent measurement of FPAR is desirable for local verification, but probably not necessary if the conditions stated by /Myneni and Williams, 1994/ are fulfilled. If the FPAR data will be used for estimtion of NPP, other parameters will probably be more uncertain than local variation in the NDVI-FPAR relationship. /Myneni et al, 1995a/ give a slightly modified relationship. It is proposed that both relationships are used for derivation of FPAR.

- To facilitate further analysis using the existing vegetation database (based on classification of SPOT data) FPAR should be derived from SPOT or Landsat TM data.

- For future monitoring it is necessary to investigate the variability of FPAR during the vegetation period. It is therefore recommended that FPAR is calculated at several occasions during the summer. A minimum of three scenes is recommended, preferably from June, July and August.

- For monitoring it is also of interest to investigate if available MODIS-products can be used (250 m surface reflectance data or FPAR-values with 1 km resolution). The advantage with MODIS-data, if giving a comparable estimate for the area, is that these data can be obtained daily or as 8-days composite products (if a high time-resolution is needed for accurate calculation of APAR). Therefore, it is recommended that MODIS daily and 8-days composites from the same date/periods as the SPOT/TM data used are procured for calculation of FPAR and comparison with the detailed results.

- PAR must be measured or obtained from other sources, for example from the data of /Bishop and Rossow, 1991/ or from measurements carried out by the Swedish Meteorological and Hydrological Institute (SMHI).

7.3.2 Data requirements

Satellite data

- SPOT or Landsat TM-data from three recording dates during June to August. (Three images will give an indication of the variations of FPAR during the summer and the time resolution needed for calculation of APAR).
- MODIS FPAR data and 250 m reflectance data (daily and 8-days products) for the same time periods for test of their usefulness for future monitoring. MODIS-data are at present free of charge.

Other data

- Measured PAR /Bishop and Rossow, 1991/ or PAR-data from other data source (e.g. SMHI).

7.4 Primary production

Net primary production for terrestrial biomes can be estimated using remotely sensed data by use of light use efficiency models or by use of more complex process models.

The basis for the light use efficiency models is that photosynthetic fixation of carbon by leaves is proportional to absorbed photosynthetically active radiation, and that the fraction of photosynthetically active radiation absorbed by the canopy (FPAR) can be remotely sensed. However, several parameters affect the light use efficiency, such as water and nutrient availability. Common approaches are therefore to use average carbon allocations coefficients or light use efficiencies for major biomes that are adjusted for water and nutrient availability.

Process models simulate biological processes affecting net primary production, such as photosynthesis, respiration, and transpiration. However, models of this type are often sophisticated and require many inputs.

Possible approaches for continued work include:

- Apply a light use efficiency model such as CASA for site-specific vegetation types. NPP is calculated as the amount of photosynthetically active radiation absorbed annually by green vegetation (APAR) multiplied by the efficiency by which that radiation is converted to plant biomass. The approach involves derivation of APAR from satellite-derived FPAR and measurements of PAR, and selection of appropriate light use efficiency values.
- Use of available MODIS NPP-products. This approach needs tests of their validity for the site-specific vegetation types. The above out-lined approach can be used for validation, or other conventional methods to calculate NPP.

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Appendix 1

Class codes for vegetation/land cover classification in Forsmark

Code 1 = outside area

Class code	Forest (not clear-cut or regeneration forest 1989)
11	Old spruce forest, mesic-wet types
12	Young spruce forest, mesic-wet types
13	Old pine forest, mesic-wet types
14	Young pine forest, mesic-wet types
15	Dry pine forest on acid rocks
21	Birch-dominated forest
23	Aspen-dominated forest
26	Ash-dominated forest
30	Mixed forest (conifers/deciduous)
31	Mixed forest/shrub on bedrock islands

Class code	Clear-cut, regeneration forest
41	Young spruce
42	Young pine
43	Unspecified young conifer
44	Birch thicket
45	Birch ticket/meadow type
46	Poor regrowth, meagre ground, boulders
50	New clear-cut

Class code	Wetlands
61	Forested wetland, spruce-dominated
62	Forested wetland, pine-dominated
63	Forested wetland, deciduous-dominated
64	Forested wetland, clear-cut
72	Open wetland, lush carpet mire/mud-bottom mire
74	Open wetland, lush lawn mire
75	Open wetland, lush lawn mire, with willow
76	Open wetland, lush lawn mire, with willow, birch
77	Open wetland, reed-dominated, less wet
78	Open wetland, reed-dominated/more lush
79	Open wetland, reed-dominated, wet

Class code	Other
81	Arable land
82	Other open land (pastures and meadows)
83	Coastal bare rocks
91	Holiday house
92	Industry
93	Lowrise house
96	Other hard surfaces
100	Water

Appendix 2

Delivery description

CD NDVI for Forsmark and Oskarshamn

Forsmark

for_stratmask		Filmapp
fors_s_ndvi_2		Filmapp
fors_s_ndvi_3		Filmapp
fors_s_ndvi_4		Filmapp
fors_s_ndvi_5		Filmapp
fors_s_ndvi_6		Filmapp
fors_tm_ndvi		Filmapp
info		Filmapp
for_stratmask.aux	5 kB	AUX-fil
for_stratmask	5 kB	CLR-fil
for_stratmask.rrd	806 kB	RRD-fil
fors_s_ndvi_2.aux	5 kB	AUX-fil
fors_s_ndvi_2.rrd	806 kB	RRD-fil
fors_s_ndvi_3.aux	5 kB	AUX-fil
fors_s_ndvi_3.rrd	806 kB	RRD-fil
fors_s_ndvi_4.aux	5 kB	AUX-fil
fors_s_ndvi_4.rrd	806 kB	RRD-fil
fors_s_ndvi_5.aux	5 kB	AUX-fil
fors_s_ndvi_5.rrd	806 kB	RRD-fil
fors_s_ndvi_6.aux	5 kB	AUX-fil
fors_s_ndvi_6.rrd	806 kB	RRD-fil
Processering av NDVI över Forsmarks studieområde	39 kB	Microsoft Word-doku...

Oskarshamn

info		Filmapp
oskar_ndvi		Filmapp
oskar_ndvi.aux	5 kB	AUX-fil
oskar_ndvi.rrd	1 532 kB	RRD-fil
Processering av NDVI över Oskarshamns studieområ...	23 kB	Microsoft Word-doku...