Numerical Weather Prediction

Options for obtaining vegetation information operationally from satellite observations

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Abstract

Following a request from Forecasting Products (FP) for the Satellite Imagery Applications Group (SIAG) to research the options for obtaining certain vegetation products operationally from satellite data, this report presents the results of the investigation. It sets out the requirements of FP, explores the satellite data and vegetation products available for use or adaptation, and suggests possible methods of creating products within the Met. Office.

The products required are essentially global Leaf Area Index (LAI) with 1 km resolution, updated weekly, and monthly updated global fractional cover, at 1 km resolution. Existing satellite data and derived products conforming to these specifications of coverage and resolution are sparse. However, a number of new products are planned within the geophysical community to make use of new satellite instruments, and these may be available in sufficient time to be of use to FP. In addition, several of the methods planned for retrieval of these new vegetation products could be adapted to allow internal development of the required products. With the recent launch of the MODerate resolution Imaging Spectroradiometer (MODIS) sensor on the National Aeronautics and Space Administration's (NASA) Earth Observation System (EOS) -AM satellite, this report recommends that the users make use of the products offered by MODIS, although some degree of internal development may be necessary to increase the temporal resolution of the fractional cover product.

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Note that ‘near-real time’ is used in this paper to mean ‘without causing significant delay to the usual updating cycle of the product’.

1 User requirements

The requirements from FP are for two vegetation products:

- Monthly updated fractional cover at 1km resolution and global coverage.
- Weekly updated LAI at 1km resolution and global coverage.

The minimum requirements acceptable are for :

- 2-yearly updated fractional cover at an absolute minimum spatial resolution of 5 km.
- LAI updated weekly for the UK, and monthly outside the UK, again at an absolute minimum spatial resolution of 5 km.

These products should be available for use by the end of 2000. Although only the UK area is needed initially, global coverage is preferable and will be needed for the future. For operational purposes, the products must be available reliably and without significant delay. It should be noted that the land area of the Earth is about 1.5×10^8 km^2, so the datasets required for global products are large.

2 Scientific background to NDVI, LAI and vegetation cover classification

Terrestrial vegetation can be remotely sensed by virtue of the optical properties of chlorophyll. Red wavelengths are absorbed, whereas near infrared wavelengths are primarily reflected. Spectral measurements made in the red (580 – 680 nm) and near infrared (IR) (725 – 1100 nm) regions of the spectrum allow certain land and vegetation characteristics to be derived. Remotely sensed data are generally used to determine land characteristics in one of two ways:

- Data may be used to produce a classification into vegetative classes from which values of biophysical properties are assigned based on information from scientific literature.
- Characteristics may be estimated statistically or by direct inversion, using remotely-sensed data.

However, the most common starting point is the derivation of the Normalised Difference Vegetation Index (NDVI).

2.1 Normalised Difference Vegetation Index

NDVI is the normalised difference between red and near IR spectral reflectances and is defined as:

$$NDVI = \frac{NIR - RED}{NIR + RED}$$ [Rouse *et al.*, 1974]

(where RED = red reflectance, NIR = near infrared reflectance)

The ratio of indices acts to minimise the noise from atmospheric effects. From NDVI, a number of other biophysical attributes can be derived, such as Leaf Area Index (LAI), and fractional cover.

2.2 Leaf Area Index

LAI is defined as half the total (two-sided) area of leaf material per unit ground area [Chen and Black, 1992]. It gives a measure of the density of foliage and is closely linked to the photosynthetic and evapotranspirative capacities of plants.

There is a strong correlation between LAI and NDVI and empirical relationships have been derived from field measurements for various vegetation types [Shippert *et al.*, 1995, Nemani and Running, 1995]. These relationships provide a way of deriving LAI, given NDVI and type of cover. Only fairly recently has a theoretical basis for the correlation between LAI and vegetation indices been established [Myneni *et al.*, 1997]. Myneni shows that NDVI can be related to the derivative of surface reflectance with respect to wavelength, and that this spectral derivative can, in turn, be related to the green leaf area index. In order to calculate LAI by this method, global land covers must first be classified into canopy structural, or biome, types. A 3-D radiative transfer model capable of simulating radiation scattering and absorption in the canopy is then used to derive an NDVI-LAI relationship for each canopy cover type [Myneni *et al.*, 1997].

Alternatively, LAI can be derived through inversion of radiative transfer models [Myneni *et al.*, 1997, Martonchik *et al.*, 1998] from spectral radiances themselves. However, different canopy structures can give rise to the same value of LAI and so canopy structures must be classified in order to solve the inverse problem. Within each biome type the radiative field is parameterised in terms of canopy transmittance, reflectance and absorbance, and these parameters are stored in a look-up table. Elements from the look-up table are used by a 1-D radiative transfer model to compute bihemispherical reflectance (BHR), bidirectional reflectance factor (BRF) and directional hemispherical reflectance (DHR) values for a wide variety of canopy/soil radiative transfer models. BHR, BRF and DHR are also computed from retrieved spectral radiances and these are compared with the modelled values. The canopy/soil models that produce the best comparison with retrieved reflectances are used to compute a weighted average LAI [Knyazikhin *et al.*, 1998].

2.3 Vegetation cover classification

Vegetation cover can be classified in a number of ways depending on the application. A classification system aims to separate types of vegetation into groups according to certain characteristics of the plants. The cover types that must be distinguished for the fractional cover product requirement are those used by the Met. Office Surface Exchange Scheme (MOSES) in the Unified Model (UM): broadleaf tree, needleleaf tree, C3 grass, C4 grass, shrub, bare soil, urban, water, and ice. These classes can be mapped from the classes of more highly-differentiated classification schemes [Cox, personal communication]. In order to classify vegetation using remote sensing, the different cover types must be distinguishable by their spectral signatures.

NDVI values tend to vary between cover types. However, the annual/seasonal variability displayed by vegetation means that vegetation type cannot be assigned from instantaneous spectral measurements. Instead, temporal profiles of spectral characteristics must be considered [Defries and Townshend, 1994]. The obvious seasonal variations are those caused by total leaf-shedding in winter months by deciduous vegetation (and regrowth in spring) and by harvesting/propagation of crops.

However, more subtle effects must be considered, such as phasing of the seasons between hemispheres and climatic and latitudinal gradients. In addition to gradual changes in vegetation cover types, dramatic changes can occur from activities/events such as deforestation, urban development, agricultural development, large-scale fires, landslides/erosion and volcanic eruptions.

Before global scale high resolution remotely sensed data became readily available, classification systems were based on cartographic sources and combinations of any data available from national databases. However, these land cover maps have coarse resolution, lack consistency and take so long to compile that updates are very difficult to perform [Running *et al*., 1994]. Remote sensing offers a consistent regime and allows frequent reclassification and updating, thus enabling changes in land cover types to be detected. The classification logic most commonly used was proposed by Running *et al*. [1994] and uses permanence of above-ground biomass, leaf longevity and leaf type as primary attributes of plant canopy structure, in a decision tree. Climate descriptors are added independently for additional information. Pattern recognition methods, which use the multispectral distinctiveness of various land cover types, are also often used.

To calculate fractional cover, each gridbox is itself divided into sub-boxes, known as tiles, and each tile can represent any of the defined cover types. This results in a potential mixture of cover types within each grid-box and defines the fractional cover. Changes in cover within a gridbox result in a change in the fractional cover rather than a change in the class of the entire gridbox, allowing for smooth changes across the model grid and better continuity.

3 Satellite data sources

3.1 Required data characteristics

In order to calculate NDVI, both red and near-IR channels are required. The user requirements state the need for global coverage at 1 km spatial resolution and monthly temporal resolution. The satellite data must additionally be available operationally and at low cost. Since there are few satellite instruments that fulfil all the requirements, instruments with the appropriate spectral bands are considered.

3.2 Data sources

Table 1 lists satellite instruments with the necessary spectral channels for vegetation product retrieval, together with details of spatial resolution, coverage and data availability wherever possible.

Instrument (satellite)	Coverage	Spatial Resolution	Availability
AVHRR-GAC (NOAA POES)	Global	12-15 km (reduced resolution)	Near-real-time from AUTOSAT
AVHRR-LAC (NOAA POES)	EC from AUTOSAT (other areas from NESDIS)	1.1 km	Near real-time from AUTOSAT (140 MB per pass)
ATSR-2 (ERS-2)	Local/global	1 km	Near-real-time for local (Tromso)
AATSR (ENVISAT)	Global	1 km	FUTURE, near-real- time
VEGETATION (SPOT-5)	Local	1.1 km	commercial
LANDSAT	Local	80 m	commercial
SEVIRI (MSG)	Europe + Africa	3 km	FUTURE, near-real-time
AVHRR-3 (EPS)	Global	1 km	FUTURE, near-real-time
MODIS (EOS)	Global	1 km	Spring 2000, near-real-time
POLDER (ADEOS-II)	Global	6 km	FUTURE

Table 1 *Possible satellite data sources including details of resolution, coverage and availability.*

Product	Organisations responsible	Coverage	Spatial resolution	Temporal resolution	Dates of availability	Costs	Method of availability	Timeliness
GVI (NDVI)	NOAA(AVHRR)	Global	15 – 20 km	Weekly, or 2 weekly	1982 - present	$75 per data set?	Tape	Delays
GIMMS NDVI	NOAA(AVHRR)	Global by continent	7 – 8 km	Monthly	1982 - 1992	?	?	N/A
Modified GVI	UMD(AVHRR)	Global	15 – 20 km	2 Weekly	1982 - 1990	?	?	N/A
Global land cover database	USGS, EROS, UNL, JRCEC	Global	1 km	Compiled only once	1992/93	free	CD	N/A
1 km product NDVI	EDC/IGBP/NASA/NOAA/ESA (AVHRR)	Global	1.1 km	10 days	Future – supposed to be complete for MODIS launch	?	CD	?
LAI	Boston U. (AVHRR)	Global	8 km	Monthly	1981 - 1991	free	ftp	N/A
NDVI	Land SAF (MSG, EPS)	Europe	1 km	Daily, or 10 days	EPS – METOP-1 launch 2003	free	GTS/ftp	Near-real-time
LAI	Land SAF (MSG, EPS)	Europe	1 km	10 days	EPS – METOP-1 launch 2003	free	GTS/ftp	Near-real-time
Land cover static map	Land SAF (MSG, EPS)	Europe	?	6 months	EPS – METOP-1 launch 2003	free	Web/ftp/ CD	Near-real-time
Land cover modification	Land SAF (MSG, EPS)	Europe	?	monthly	EPS – METOP-1 launch 2003	free	Web/ftp/ CD	Near-real-time
Land cover	NASA (MODIS)	Global	1 km	quarterly	Summer 2001	free	ftp	Near-real-time
Land cover change	NASA (MODIS)	Global	1 km	quarterly	Summer 2001	free	ftp	Near-real-time
LAI	NASA (MODIS)	Global	1 km	Daily/8 day	Summer 2000	free	ftp	Near-real-time

Table 2 *Existing and planned vegetation products available from various sources. Shaded boxes indicate that these product attributes satisfy the user requirements (or in the case of 10 day temporal resolution very nearly satisfy). Question marks indicate information not yet obtained*

4 Products

A list of existing and planned vegetation products is given in table 2, along with some details of the attributes of each product. An indication is also given of the extent to which each product fulfils the user requirements, but this will be considered further in section 6.

4.1 Current and historical products

4.1.1 Global Vegetation Index (GVI)

This is a widely available global product, from the National Oceanic and Atmospheric Administration (NOAA), which uses Advanced Very High Resolution Radiometer Global Area Coverage (AVHRR GAC) data. The resolution is coarse (greater than 15 km) with composited images representing 7 day periods, and has been produced weekly and biweekly since 1982 [Townshend, 1994a]. However, in addition to its coarse resolution, the NOAA GVI product has a number of limitations. Raw digital numbers rather than calibrated reflectances are used to calculate NDVI, there is no cloud screening procedure and Difference Vegetation Index (DVI) rather than NDVI is used to compile the weekly composites, resulting in selection of pixels more affected by atmospheric effects [Goward *et al*., 1994, Townshend *et al*., 1993].

4.1.2 Global Inventory Monitoring and Modelling Systems product (GIMMS)

The GIMMS NDVI product, from NASA's Goddard Space Flight Center (GSFC), again uses AVHRR GAC data, but by reprojecting the data onto an equal area projection and resampling by continent, a spatial resolution of about 8 km is achieved. This product has been produced from 1982–1992, but only on a monthly basis. Several of the limitations inherent in the GVI product are overcome. The digital numbers are converted to at-satellite reflectances using calibration data, a cloud detection procedure is implemented and NDVI values are used in the compilation of 15-day composites. [Townshend, 1994a]

4.1.3 University of Maryland improved GVI product (Modified GVI)

This dataset has been produced by reprocessing the NOAA GVI data record from 1983 – 1991. The data are therefore not available for the current time. The original AVHRR data have been mapped to a consistent projection and radiometrically calibrated to spectral reflectance. NDVI rather than DVI has been used to compute 2-weekly composites, thus reducing cloud contamination. Quality indicators have also been included, and a significant improvement has been made over the original GVI data. [Goward *et al*., 1994]

4.1.4 Global land cover characteristics database

This has been produced by the U. S. Geological Survey's (USGS) Earth Resources Observation System (EROS) Data Center, the University of Nebraska-Lincoln (UNL), and the Joint Research Centre of the European Commission. It is derived from 1 km AVHRR data spanning a 12-month period (April 1992 – March 1993) and uses a multitemporal unsupervised classification of NDVI data, with postclassification refinement using multisource earth science data. Five different datasets are derived, each containing vegetation classes appropriate for its application. Of these the 17-class International Geosphere Biosphere Programme (IGBP) Land Cover Classification is the simplest scheme and is being assessed within the Met. Office for inclusion in the UM.

4.2 Future products expected

A number of land products are being developed at present that may be available in sufficient time for consideration. These plan to use data from both existing and as yet unlaunched satellite instruments.

4.2.1 AVHRR 1 km product

The EROS Data Center (EDC), IGBP, NASA, NOAA, and the European Space Agency (ESA) are collaborating to develop a 1 km resolution global NDVI product from AVHRR data, in readiness for the preparation of MODIS products. Archiving of global Local Area Coverage (LAC) raw data by the collaboration of many receiving stations has already taken place, but the NDVI product appears to be still in the development process, and it is not yet known whether near-real-time data will be available.

4.2.2 Land Surface Analysis SAF products

The most recent of Eumetsat's Satellite Application Facilities (SAF), the Land Surface Analysis SAF started in September of this year, under the management of the Portuguese Meteorological Institute. A comprehensive set of vegetation products is proposed in EUM/J-STG-AFG/14/99/DOC/03+Annex [1999] for development. The SAF plans to make use of both SEVIRI on Meteosat Second Generation (MSG) and AVHRR-3 on Eumetsat Polar Systems (EPS) sensors when launched, in combination with data from MODIS, Multiangle Imaging SpectroRadiometer (MISR) and VEGETATION. NDVI will be used to derive LAI at 1 km resolution, every 10 days, static land cover maps every 6 months, and land cover modification monthly. The proposal indicates the possibility of both European/National area and global coverage and this should certainly be possible with the combination of high temporal resolution geostationary data with global coverage polar orbiter data. Plans are also discussed to incorporate data from higher spatial resolution satellite sensors such as Landsat Thematic Mapper (TM) and SPOT HRV.

4.2.3 MODIS Products

MODIS was launched on Terra (EOS-AM) by NASA GSFC on 18 December 1999. LAI, land cover and land cover change products are under development. While LAI should be operational by late summer 2000, a full year of operation is necessary before land cover data can be generated, and so the land cover and change products will not be available until summer 2001.

LAI will be retrieved from atmospherically corrected BRF and provided globally at 1 km spatial resolution on a daily and 8-daily basis. The retrieval method of Myneni et al. [1995] and Knyazikhin et al. [1998], described in section 2.2 will be used, in which a 3-D radiative transfer model is used to derive simple spectral and angular biome-specific signatures of vegetation canopies. The radiative transfer problem is split into several independent and simpler sub-problems, the solutions of which are stored in the form of a look-up table and are then used to retrieve LAI [Justice *et al.*, 1998]. A back-up method is planned that will estimate LAI from NDVI (as in Myneni *et al.* [1997]).

Global land cover and cover change will be retrieved at 1 km and ¼ degree resolution quarterly. Classification will be achieved using supervised artificial neural networks and detailed decision trees and will be based on the 17-class IGBP system. The land cover change parameter is derived by combining changes in observations of multitemporal and multispectral signals with models of vegetation change mechanisms to indicate both the type and intensity of the change. The retrieval method uses a combination of techniques to detect change, including differences in local spatial texture between successive dates and appearance of linear features. The at-launch product will be derived from AVHRR 1-km data until MODIS can provide long enough time series to show cycles of vegetation phenology. [Justice *et al.*, 1988]

4.2.4 ATSR Products

The Along Track Scanning Radiometer (ATSR) aboard ERS-2 provides global high resolution data in the appropriate spectral bands for deriving vegetation information. It is also very well calibrated, with narrow bands that reduce contamination from ozone and water vapour. Although no vegetation products are retrieved from ATSR at present, a vegetation index product is under consideration for production in the future [C. Mutlow, private communication]. At present brightness temperatures and reflectances at 1 km spatial resolution are available in near-real-time from Tromso Satellite Station for the UK area and global data could be made available in near-real-time if necessary.

5 Development of products within the Met. Office

Should none of the available or planned products satisfy the requirements of the users, various methods are feasible for the development of the required products within the Met. Office. These methods all rely on the availability of suitable satellite data and here the options are limited as global high resolution operationally available data are required. Of the list shown in Table 1, only ATSR-2 currently provides, and MODIS and AATSR will fairly soon provide, data at 1 km resolution at near-real time. AVHRR LAC data are available for the European area, but global data is not at sufficiently high spatial resolution (12-15 km for GAC). However global composites of 1 km LAC data are planned for the future, as discussed in section 4.2.1. METOP will provide global data at around 1 km resolution after 2003.

5.1 Development of NDVI

Theoretically NDVI should be easy to calculate from satellite reflectances, given the relation:

$$NDVI = \frac{NIR - RED}{NIR + RED}$$ [Rouse *et al.*, 1974]

(where RED = red reflectance, NIR = near infrared reflectance)

However, the satellite data must first be processed and unless processing software is available with the data, this involves a considerable effort. Initially, navigation algorithms must be used to geolocate pixels and the navigation must also be monitored. The data must then be remapped to the chosen projection. Sensor calibration of individual channels must be implemented and digital numbers converted to spectral reflectances to enable NDVI calculation. Atmospheric corrections must be applied and a method employed to screen for clouds, after which NDVI can be calculated. To produce a cloud-free dataset several days of data must be composited. Since higher NDVI values tend to represent lower aerosol/cloud contamination, the highest NDVI values should be used in the composite. However, data with scan angles greater than 42 degrees should not be included since bi-directional effects mean that the large NDVI from these pixels may be due in part to back-scattering [James and Kalluri, 1994]. Automated checks for out of range or missing data should also be performed throughout the processing, as a quality control measure.

5.2 Development of LAI product

As discussed in section 2.2 there are a number of ways of retrieving LAI from remotely sensed data, most of which are derived from NDVI. These are:

- Use of empirical type-specific relationships between NDVI and LAI stated in scientific literature.
- Regression analysis, using radiative transfer modelling of type-specific NDVI-LAI relationships.
- Inversion of radiative transfer models, using spectral and angular signatures of radiances.

The first two options require the pre-calculation of NDVI or availability of a distributed NDVI product, whereas the third option uses measured radiances. All three methods require a land cover classification of suitable spatial resolution.

5.2.1 Empirical relationships

Nemani and Running [1995] cite several NDVI-LAI relationships that have been established empirically:

- For grass: $LAI = (NDVI \times 1.71) + 0.48$ [Asrar *et al.*, 1985]
- For needle leaf canopies: $LAI = (NDVI/0.31) \times 0.26$ [Spanner *et al.*, 1990; Nemani and Running, 1989]
- For broadleaf canopies: $LAI = (NDVI/0.26) \times 2$ [Pierce *et al.*, 1993]

Although simple empirical relations do not account for problems like variations in background, atmospheric influences and viewing geometry, they do yield seasonal variations in LAI since multitemporal cycling is evident in NDVI. Empirical relationships such as these could be used to perform a simple LAI retrieval from an NDVI product, given that vegetation type classification has already been performed. Suggestions for performing vegetation type classification are given in section 5.3 and NDVI products will soon exist from AVHRR and MODIS data, hence, despite its limitations, this is potentially a fast and computationally cheap method for the calculation of LAI. Figure 1 shows schematically the procedure for deriving LAI in this manner.

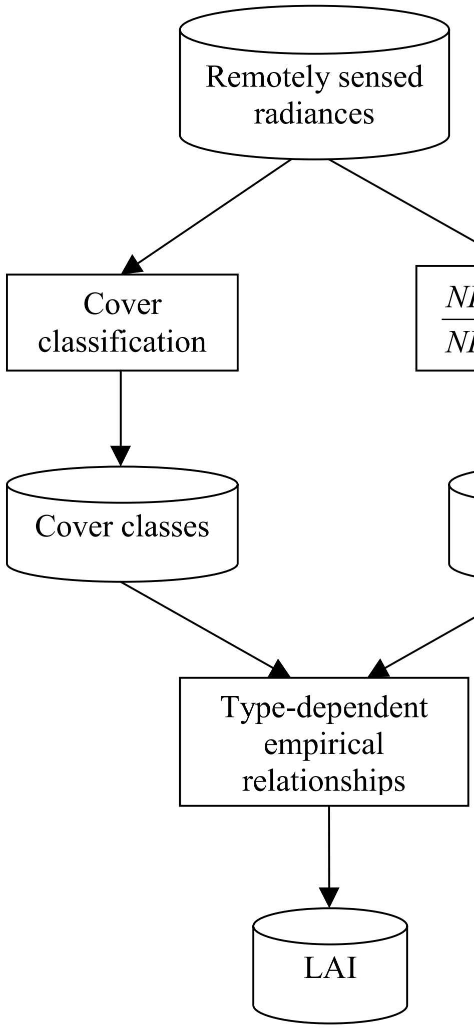

Figure 1. *Schematic representation of the retrieval of LAI using empirical relationships between NDVI and LAI.*

5.2.2 Regression analysis

As in section 5.2.1 above, classification of land cover into canopy types is a prerequisite for this method. LAI is again retrieved through its relationship with NDVI, but rather than use empirical relationships, the type-specific NDVI-LAI relationships are derived using a 3-D radiative transfer model. Myneni et al. [1997] describe the retrieval method, for the estimation of LAI from atmospherically corrected NDVI observations, and give details of the 3-D model formulation. The six cover types utilised by Myneni et al. [1997] are grasses and cereal crops, shrubs, broadleaf crops, savanna, broadleaf forests, and needleleaf forests, and these are defined in terms of parameter values used by radiative transfer models. The model is being used extensively by the MODIS science team and the above method will be implemented in the back-up algorithm for calculating LAI by MODIS. This method of retrieving LAI would be suitable for use along with NDVI and fractional cover products and is a more thorough approach than that using the empirical relationships. This method is illustrated schematically in Figure 2.

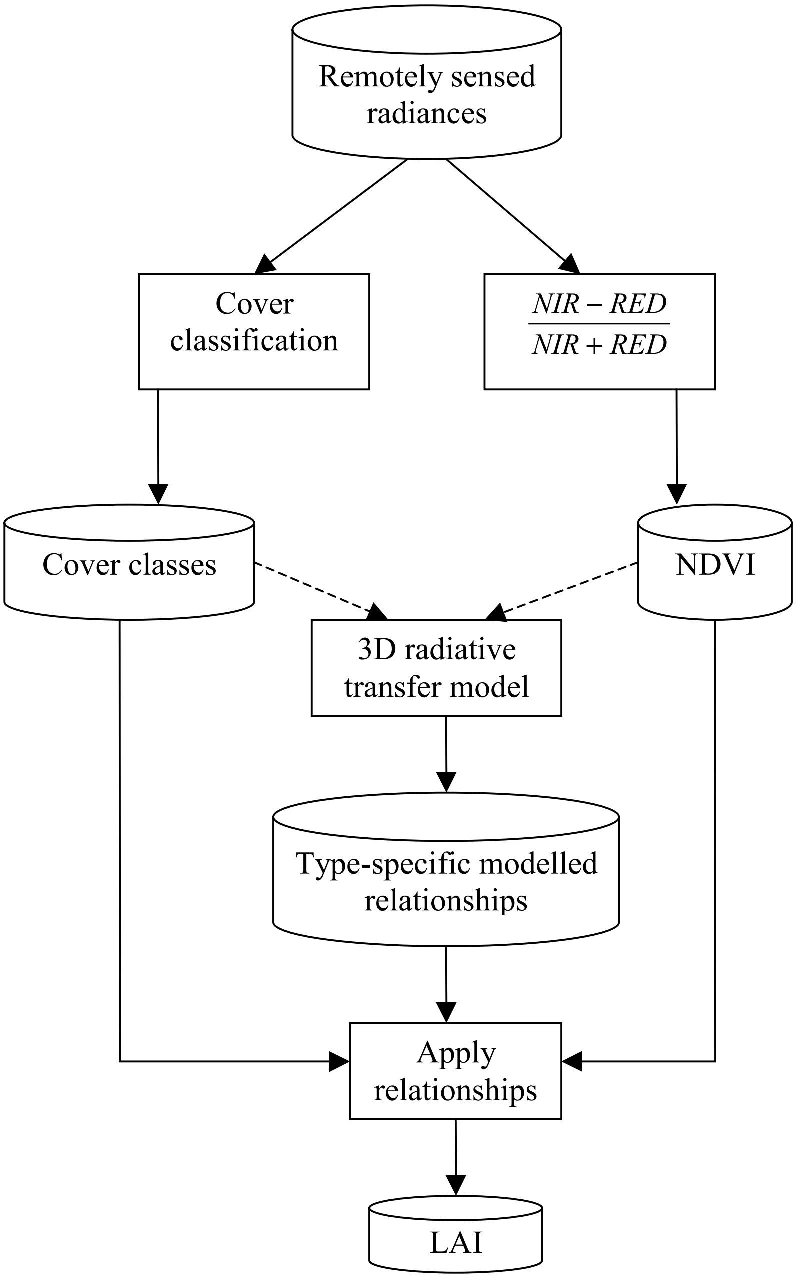

Figure 2. *Representation of the retrieval of LAI using regression analysis to model type-specific NDVI-LAI relationships. The dashed arrows indicate a procedure that is not carried out continuously.*

5.2.3 Inverse radiative transfer modelling

Inversion of radiative transfer models for retrieval of LAI was discussed in section 2.2 and details can be found in Martonchik *et al*. [1998], Knyazhikin et al. [1998]. This method is able to derive LAI without the prior derivation of NDVI, however land cover classification is a prerequisite. In this respect it is less restrictive than the methods using LAI-NDVI relationships. It is also the primary retrieval method to be used by the MODIS team to derive their LAI product. This method is an improvement on those that use simple relationships between NDVI and LAI as these ignore much of the variation in canopy architecture and soil reflectance. Use of multiangle data such as MISR data also allows a more accurate determination of surface directional reflectance properties.

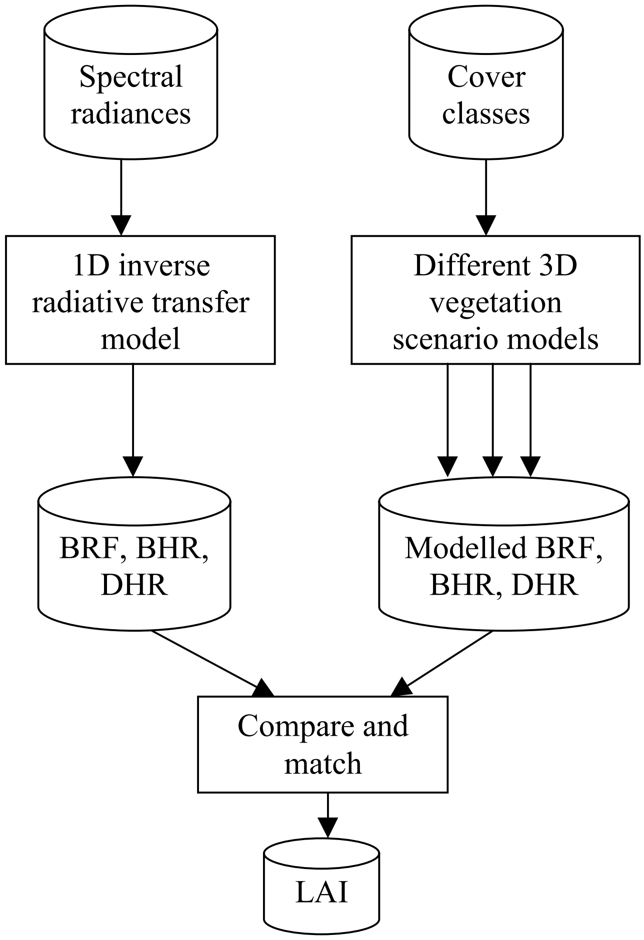

Figure 3. *Representation of the derivation of LAI using inverse radiative transfer modelling. Multiple arrows denote many values.*

The procedure uses as input measured canopy reflectance data from MODIS, MISR, or both MODIS and MISR. 1-D inverse radiative transfer and 3-D soil/canopy radiative transfer models must also be used and these are described in Knyazhikin et al. [1998] and references therein. ATSR data may also provide sufficient angular information to allow adaptation of this method. A schematic representation is shown in Figure 3.

5.3 Development of fractional cover product

As discussed in section 2.3 classification of land cover can be a lengthy process and at present no operational regularly updated product exists. However, several of the methods planned for future products could feasibly be modified, either to produce an entirely new product or to improve and update existing products.

The classification logic described in section 2.3, proposed by Running et al. [1994] could be adopted to produce an operational fractional cover product. This decision tree could be implemented using current satellite systems, such as AVHRR, and requires use of NDVI product. However, in order to classify land cover through remote sensing, an entire seasonal cycle must be observed. A historical record of NDVI would be necessary to derive 'current time' classification. This could be achieved using a product such as GVI, although this doesn't give 1 km spatial resolution. The possible planned AVHRR 1 km global product may be more appropriate.

It would, however, be easier to use an existing classification map, and develop a method for detecting land cover change. A method such as this could be of particular use in combination with land cover products that are not available at the required monthly temporal resolution. The MODIS land cover change product will only be available quarterly; by diagnosing land cover change for the months between the quarterly product releases, a product could be developed that would fulfil the user requirements.

A fairly simple method for cover change detection could probably be implemented given knowledge of the following (in brackets are examples of data/products providing the required information):

- Existing land cover classification for initial information (given by MODIS land cover product and cover change from previous quarter.)
- Recent changes in land cover to indicate tendencies of change (given by MODIS land cover change from the previous quarter.)
- Daily or weekly NDVI values for analysing changes in reflective behaviour of the canopy (given by MODIS daily NDVI product.)
- Temporal profiles of NDVI which display the seasonal behaviour of each canopy type (examples are given in Defries and Townshend (1994) although any year-long record of NDVI for the different vegetation classes would be appropriate.)

The proposed cover change detection method consists of detecting that a change has taken place, diagnosing the change and finally implementing the change in the land cover classification map. These procedures are discussed below:

5.3.1 Detecting cover change

Since each vegetation type has a different seasonal NDVI signal, especially in this case where the cover classes are fairly broad, it should be possible to ascertain when the vegetation type over a particular geographical area has changed, given the seasonal NDVI signals of all the possible cover classes. The starting point would be a global classification map and the most recent cover change diagnostic. The following decisions could be involved in ascertaining that a change in cover type has indeed taken place for a particular pixel:

- Has the NDVI signal deviated significantly from that expected for the cover type present within the pixel?
- Is the pixel within an area showing cover change tendencies in the previous diagnosis?
- Is the cover type one which is likely to change (*e.g.* forest, crops)?

- Is the pixel in a geographical location in which there is likely to be cover type changes?

5.3.2 Diagnosing cover change

After it has been ascertained that a change in vegetation type has taken place, the change must be diagnosed so that a new cover type can be represented by the pixel. Some factors that will affect the diagnosis are:

- To which cover type does the retrieved NDVI signal correspond?
- Is the suspected cover change likely/allowed?
- Are there pixels nearby demonstrating the same change?

If all possible changes were allowed for every pixel, the procedure would not be effective and would certainly be extremely costly computationally. However, in reality the options for changes in vegetation type are considerably restricted by our knowledge of the behaviour of the ecosystem. In fact, on a timescale of 1 month changes in vegetation are very limited. Dramatic changes may occur from activities or events such as deforestation, farming, fires, and urbanisation, but slowly evolving systems such as the development of forests from shrub/scrubland will not occur on a monthly timescale. Choices may also be limited by the geographical location of the pixel, for instance a change from vegetated to urban is extremely unlikely in an inaccessible/unpopulated area of the globe. All of these limitations to vegetation change could be combined into a field of available choices, which could then be applied to the global NDVI data field pixel by pixel. This "choice field" would have to be updated to account for long term trends in vegetation cover, but on a much longer timescale than 1 month.

The major work involved in generating such a product would clearly be in developing the procedure for the derivation of the "choice field". Once the field of available choices has been generated, the work involved in applying it to the data field each month and implementing any changes is expected to be minimal. It would be necessary to perform trials to assess the feasibility of diagnosing the change from LAI or NDVI alone. However, it is expected that the choices for changes are sufficiently narrow that the proposed method would be viable.

6 Conclusions and recommendations

6.1 Possible data and products for the UK area

At present both AVHRR (LAC) and ATSR-2 data are available operationally at 1 km spatial resolution for the UK area. AVHRR LAC data are processed by the AUTOSAT team within the Met. Office (with data volumes of 140 Mbytes per pass) and ATSR-2 data are available through the Tromso Satellite Station ATSR Near Real Time Service. These data could be used to derive NDVI, LAI and fractional cover products, as suggested in section 5. No current products exist that provide the required products operationally at 1 km spatial resolution, however, the NOAA GVI product is available at 15 – 20 km resolution. Landsat and VEGETATION are both commercial satellites and so data from them would not be free.

6.2 Possible data and products for global coverage

Global ATSR-2 data at 1 km spatial resolution are not at present available in near-real time. However, the potential for this provision exists. AATSR data should be available globally, at 1 km resolution in near-real-time, soon after ENVISAT launch (currently scheduled for 2001). These data could be used to derive NDVI, LAI and fractional cover products, as suggested in section 5. The most promising products being developed are those from the planned EOS, MSG and EPS satellites. MODIS was launched on the EOS-AM platform in December 1999 and should provide global 1 km LAI by late summer 2000, and land cover, and land cover change products by summer 2001, free of charge, via ftp. The at-launch land cover, derived from AVHRR data, is available in the interim period before MODIS land cover becomes available. The LAI product will be available daily or every 8 days and fulfils the user requirements. However, the land cover change product is only available quarterly. Development of an internal land cover change detection method, as proposed in section 5.3, could be adopted to provide additional updates between the quarterly product release times. The Land Surface Analysis SAF also plans to deliver LAI and land cover products using data from SEVIRI (MSG) and AVHRR-3 (EPS). However, it is not known when these products will be available, bearing in mind that METOP-1 will not be launched until at least 2003.

6.3 Recommendations

It is clear that there is very little in the way of data and products available operationally at the present time. Although it is theoretically feasible to develop the products required within the Met. Office, at least for the UK area, processing raw polar orbiter data can be a complex and lengthy process, hence it is desirable to use 'ready-made' products where possible, even if adaptation is needed to fulfil the user requirements. It is recommended here that use should be made of the MODIS products when they become available (with some in-house enhancements, if necessary), rather than developing new products from scratch within the Met. Office. The LAI product fulfils all the user requirements and the land cover/land cover change products fulfil all but temporal resolution requirements. Development of a land cover change product should be feasible in order to provide more frequent land cover updates. Products under development by the Land Surface Analysis SAF should also be considered for use in the future.

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8 Web references

This list contains addresses for relevant web sites (accurate at the time of writing) that may be of further use/interest. Information from many of these sites was used in compiling this report.

http://cybele.bu.edu/	Climate, Vegetation and Remote Sensing group (Boston University)
http://polder@www-projet.cst.cnes.fr:8060/	POLDER mission
http://www.inform.umd.edu/geog/LGRSS/	Laboratory for Global Remote Sensing Studies (UMD)
http://www.nmw.ac.uk/ite/	Institute of Terrestrial Ecology homepage
http://ltpwww.gsfc.nasa.gov/MODIS/MODIS.html	MODIS homepage
http://www.eumetsat.de/en/index.html?area=left4.html&body=/en/area4/topic3.html&a=430&b=1&c=400&d=400&e=0	Eumetsat SAFs
http://daac.gsfc.nasa.gov/CAMPAIGN_DOCS/ISLSCP/islscp_i1.html	International Satellite Land Surface Climatology Project
http://daac.gsfc.nasa.gov/CAMPAIGN_DOCS/LAND_BIO/GLBDST_main.html	Global Land Biosphere Data and Resources homepage
http://www.ciesin.org/TG/HDP/igbp.html	International Geosphere Biosphere Programme
http://earth.esa.int/	ESA Earthnet Online homepage
http://www.saa.noaa.gov/help/data.html	Satellite Active Archive (NOAA)
http://www.atmo.arizona.edu/land/uofa_land.html	Land Surface Group (University of Arizona)
http://esip.umiacs.umd.edu/glcf_data.html	UMD Global Land Cover Faculty homepage
http://www.tss.no/	Tromsoe Satellite Station homepage

http://www.jrc.cec.eu.int/	Joint Research Centre
http://yyy.tksc.nasda.go.jp/Home/Projects/ADEOS-II/index_e.html	ADEOS-II homepage (NASDA)
http://www.earth.nasa.gov/missions/index.html	Earth Science Missions (NASA)
http://edcwww.cr.usgs.gov/eros-home.html	EROS homepage
http://landsat7.usgs.gov/	Landsat7 homepage
http://edcwww.cr.usgs.gov/landdaac/index.html	EDC Distributed Active Archive Center
http://edcwww.cr.usgs.gov/landdaac/1KM/1kmhomepage.html	Global Land 1-KM AVHRR Project
http://www.landsaf.org/frames_meteoe.htm	Land Surface Analysis SAF
http://www.nrsc.co.uk/	National Remote Sensing Centre
http://envisat.estec.esa.nl/	Envisat-1 homepage (ESA)
http://www.le.ac.uk/physics/research/eos/aatsr/index.html	AATSR homepage
http://www.atsr.rl.ac.uk/	ATSR homepage

9 Acronyms, Research groups

AATSR	Advanced Along Track Scanning Radiometer
ATSR	Along Track Scanning Radiometer
AVHRR	Advanced Very High Resolution Radiometer
BHR	bihemispherical reflectance
BRF	bidirectional reflectance factor
DHR	directional-hemispherical reflectance
DVI	Difference vegetation index
EDC	EROS Data Center
EOS	Earth Observation System
EPS	Eumetsat Polar Systems
EROS	Earth Resources Observation System
ESA	European Space Agency
FP	Forecasting Products
GAC	Global Area Coverage
GSFC	Goddard Space Flight Center
GIMMS	Global Inventory Monitoring and Modeling Systems
GVI	Global Vegetation Index
HDRF	hemispherical-directional reflectance factor
IGBP	International Geosphere Biosphere Programme
LAC	Local Area Coverage
LAI	leaf area index
MISR	Multiangle Imaging SpectroRadiometer
MODIS	MODerate resolution Imaging Spectroradiometer
MOSES	Met. Office Surface Exchange Scheme
MSG	Meteosat Second Generation
NASA	National Aeronautics and Space Administration
NDVI	normalised difference vegetation index
NOAA	National Oceanic and Atmospheric Administration
POLDER	POLarization and Directionality of the Earth's Reflectance

SAF	Satellite Application Facility
SIAG	Satellite Imagery Applications Group
TM	Thematic Mapper
UM	Unified Model
UMD	University of Maryland
UNL	University of Nebraska-Lincoln
USGS	U. S. Geological Survey