Available online at www.sciencedirect.com
ScienceDirect
Advances in Space Research 39 (2007) 100–104
ADVANCES IN SPACE RESEARCH (a COSPAR publication)
www.elsevier.com/locate/asr

Evaluation of the MERIS terrestrial chlorophyll index (MTCI)

J. Dash *, P.J. Curran

School of Geography, University of Southampton, Southampton, SO17 1BJ, United Kingdom

Received 1 October 2004; received in revised form 1 September 2005; accepted 15 February 2006

Abstract

The Medium Resolution Imaging Spectrometer (MERIS), one of the payloads on Envisat, has fine spectral resolution, moderate spatial resolution and a 3-day repeat cycle. This makes MERIS a potentially valuable sensor for the measurement and monitoring of terrestrial environments at regional to global scales. The red edge, which results from an abrupt reflectance change in red and near-infrared (NIR) wavelengths has a location that is related directly to the chlorophyll content of vegetation. A new index called the MERIS terrestrial chlorophyll index (MTCI) uses data in three red/NIR wavebands centered at 681.25, 708.75 and 753.75 nm (bands 8, 9 and 10 in the MERIS standard band setting). The MTCI is easy to calculate and can be automated. Preliminary *indirect* evaluation using model, field and MERIS data suggested its sensitivity to chlorophyll content, notably at high values. As a result this index is now a standard level-2 product of the European Space Agency.

For *direct* MTCI evaluation two approaches were used. First, MTCI/chlorophyll content relationships were determined using a chlorophyll content surrogate for sites in southern Vietnam and second, MTCI/chlorophyll relationships were determined using actual chlorophyll content for sites in the New Forest, UK and for plots in the greenhouse. Forests in southern Vietnam were contaminated heavily with herbicides during the Vietnam War. This led to a long term decrease in chlorophyll content within forests that have long since regained full canopy cover. The amount of herbicide dropped onto the forests between 1965 and 1971 was used as a surrogate (inverse) for contemporary chlorophyll content and was related to current MTCI at selected forest sites. The resulting relationship was both strong and negative. Further per-pixel investigation of the MTCI/herbicide concentration relationship is under way for large forest regions. In the second approach MTCI was related directly to chlorophyll content at two scales and the initial relationships were both of strong and positive. Further plans involve MTCI evaluation at local, regional and eventually global scales.
© 2006 COSPAR. Published by Elsevier Ltd. All rights reserved.

Keywords: Chlorophyll; Red edge; MERIS; MTCI

1. Introduction

Chlorophyll is one of the more important foliar biochemicals and the content within a vegetation canopy is related positively to both the productivity of that vegetation and the depth and width of the chlorophyll absorption feature in the reflectance spectra. The long wavelength (red) edge of this absorption feature moves to even longer wavelengths with an increase in chlorophyll content (Curran et al., 1990; Filella and Peñuelas, 1994; Munden et al., 1994) and the red edge position (REP) can be defined as the point of maximum change in reflectance along this edge (Horler et al., 1983). However, there are two problems with the use of REP to estimate foliar chlorophyll content from a spaceborne sensor. First, the methods used to estimate REP have been designed for use on continuous spectra without thought for standardisation or automation (Dawson and Curran, 1998). Second, REP is not an accurate indicator of chlorophyll content at high chlorophyll contents because of the asymptotic relationship between REP and chlorophyll content (Jago et al., 1999).

The Medium Resolution Imaging Spectrometer (MERIS) on the European Space Agency (ESA) Envisat satellite has fine spectral resolution, moderate spatial resolution and a three day repeat cycle (Table 1). This makes MERIS a potentially valuable sensor for the measurement and monitoring of terrestrial environments at regional to

* Corresponding author. Tel.: +44 7717503411.
E-mail address: jadu@soton.ac.uk (J. Dash).

0273-1177/$30 © 2006 COSPAR. Published by Elsevier Ltd. All rights reserved.
doi:10.1016/j.asr.2006.02.034

Table 1
Geometric, spectrometric and radiometric properties of MERIS data

Sensor parameters	Values
Field-of-view	68.5° centred around nadir
Swath width	1150 km
Localisation accuracy	400 m (without the use of landmarks)
Spatial resolution	Full resolution – 300 m Reduced resolution – 1200 m
Band to band registration	<0.1 FR pixel
Spectral range	390–1040 nm
Spectral sampling interval	1.25 nm
Spectral resolution	1.8 nm
Band transmission capacity	15 bands programmable in position and width
Band width	Programmable from 1.25 nm up to 30 nm
Radiometric accuracy	<2% in reflectance
Dynamic range	Up to bright clouds (100% reflectance)
Signal-to-noise ratio	1650:1 (@412.5 nm) for typical ocean signal

global scales (Rast et al., 1999). In the standard band setting, it has five discontinuous wavebands in red and near infrared (NIR) wavelengths with band centres at 665, 681.25, 708.75, 753.75 and 760.625 nm.

Two techniques have been used to estimate chlorophyll content using the red edge position on discontinuous (simulated) MERIS spectra: Lagrangian interpolation (Dawson, 2000) and linear interpolation (Clevers et al., 2002). Both produce a different value of REP from the same dataset and neither offer the automated, one-step procedure that would be required for the processing of a large volume of data at, for example, a ground receiving station. Therefore a new index, the MERIS Terrestrial Chlorophyll Index (MTCI), was developed for estimating chlorophyll content from MERIS data (Dash and Curran, 2004).

This paper reports on two planned approached to the evaluation of MTCI. First, MERIS data and a surrogate of chlorophyll content for sites in southern Vietnam; second, MERIS data and actual chlorophyll content for sites in the New Forest, UK and plots in a greenhouse.

2. The MERIS terrestrial chlorophyll index

Two criteria for the design of a chlorophyll index using MERIS data are: first, it should be easy to calculate from MERIS data recorded at the standard band setting and second, it should be sensitive to a wide range of chlorophyll contents. *Illustrative* vegetation reflectance spectra (model output) overlain with MERIS bands 8, 9 and 10 are given in Fig. 1, with chlorophyll content increasing from spectrum 1 to spectrum 4. An increase in absorption due to an increase in chlorophyll content is seen in the wavelength range 650–700 nm.

Reflectance increases sharply as we move from MERIS band 8 to band 10 for a particular chlorophyll content (Fig. 1). However, comparison of the four illustrative reflectance spectra reveals two important features: (i) with an increase in chlorophyll content the difference in reflectance between band 8 and band 9 decreases gradually and (ii) with an increase in chlorophyll content the difference in reflectance between band 9 and band 10 increases gradually. A new index, the MERIS Terrestrial Chlorophyll Index (MTCI) is a ratio of the difference in reflectance between band 10 and band 9 and the difference in reflectance between band 9 and band 8 of the MERIS standard band setting

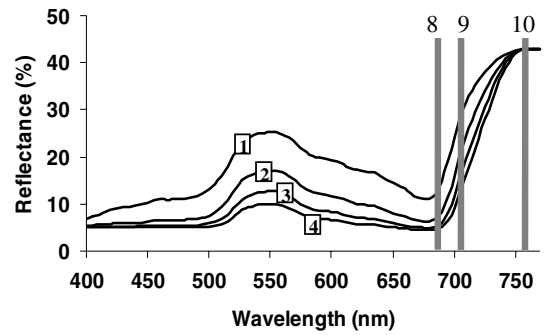

Fig. 1. Illustrative vegetation reflectance spectra at four chlorophyll contents (model output), overlain with the position of MERIS bands 8, 9 and 10.

$$\mathrm{MTCI} = \frac{R_{\mathrm{Band10}} - R_{\mathrm{Band9}}}{R_{\mathrm{Band9}} - R_{\mathrm{Band8}}} = \frac{R_{753.75} - R_{708.75}}{R_{708.75} - R_{681.25}}, \quad (1)$$

where $R_{753.75}$, $R_{708.75}$, $R_{681.25}$ are reflectance in the centre wavelengths of band 8, 9 and 10 in the MERIS standard band setting.

3. Indirect MTCI evaluation methods

Data from vegetation reflectance models (based on radiative transformation theory) and laboratory and field measurements (of leaves and canopies, respectively) were used for an indirect quantitative evaluation of the MTCI, in addition real MERIS data were used for an indirect qualitative evaluation the MTCI.

3.1. Model data

Vegetation reflectance obtained from LIBSAIL combination of LIBERTY (Leaf Incorporating Biochemistry Exhibiting Reflectance and Transmittance Yield) (Dawson et al., 1998) and SAIL (Scattering by Arbitrary Inclined Leaves) (Verhoef, 1984) spectra for simulated MERIS band positions over a wide range of chlorophyll contents (10–400 mg m^{-2}) are shown in Fig. 2a. Estimates of MTCI and REP for each spectrum are given in Fig. 2.

The asymptotic relationship between REP and chlorophyll content (Fig. 2b) suggested insensitivity to high chlorophyll contents; however, the near-linear relationship between MTCI and chlorophyll content (Fig. 2b), suggested sensitivity to high chlorophyll contents.

3.2. Field data

Canopy reflectance spectra and chlorophyll content data had been collected for monospecific canopies formed from Douglas-fir (*Pseudotsuga menziesii*) and bigleaf maple

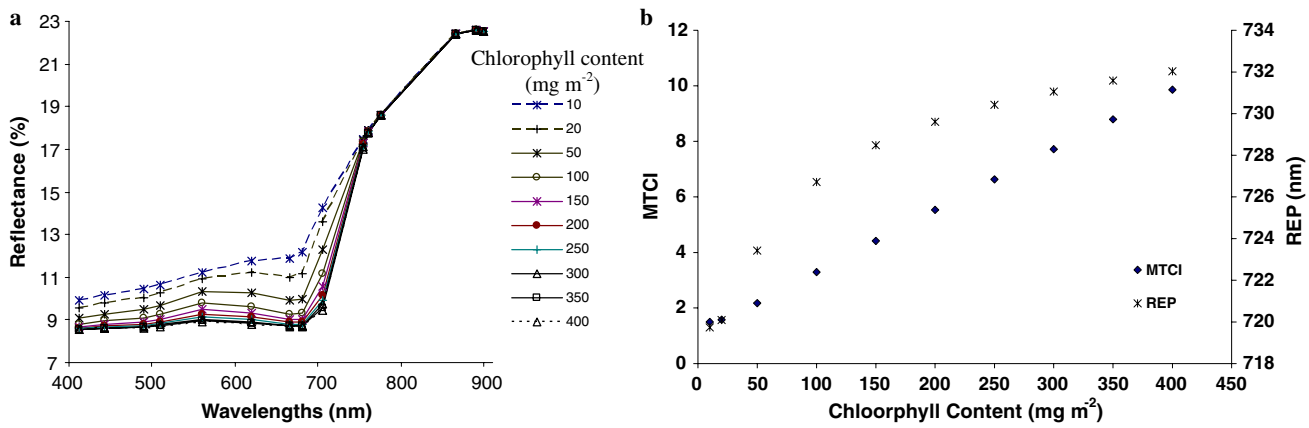

Fig. 2. (a) Reflectance spectra for MERIS data at the standard band settings, simulated using the LIBSAIL model for a wide range of chlorophyll contents; (b) relation between chlorophyll content and MTCI and chlorophyll content and REP for the same range of chlorophyll contents.

(*Acer macrophyllum*) seedlings as a part of NASA's 1992–1993 ACCP (Accelerated Canopy Chemistry Program) (Yoder and Johnson, 1999).

For Douglas-fir the coefficients of determination (r^2) were 0.64 and 0.62 between chlorophyll content and first MTCI and second REP. Similarly, for maple the r^2 were 0.72 and 0.62 between chlorophyll content and first MTCI and second REP. In both cases, the regression line between MTCI and chlorophyll content had a slightly steeper slope than the regression line between REP and chlorophyll content. This suggested that MTCI was more sensitive than REP to chlorophyll content.

3.3. MERIS data

A subset of a MERIS image acquired on 19th October 2002 was extracted for the New Forest, Hampshire, UK and NDVI, REP and MTCI images were estimated. The area comprises coniferous and deciduous woodland along with heath, meadows, agricultural land, urban areas and water. The NDVI image delineated three broad zones (i) vegetated with high NDVI (and assumed high chlorophyll content), (ii) vegetated with intermediate NDVI (and assumed lower chlorophyll content) and (iii) non-vegetated. The REP image identified some variation within these broad NDVI zones; however, the MTCI image identified greater variation within the broad NDVI zones and this level of variation did not decline with increasing NDVI. This suggested that MTCI was likely to be more sensitive than REP to high values of NDVI and thereby chlorophyll content.

4. Direct MTCI evaluation methods

Two approaches were used for direct MTCI evaluation. First, MTCI/chlorophyll content relationships were determined using a surrogate of chlorophyll content for sites in southern Vietnam and second, MTCI/chlorophyll relationships were determined using actual chlorophyll content for sites in the New Forest, UK and for plots in the greenhouse.

4.1. MTCI/chlorophyll content (surrogate) relationship in southern Vietnam

Fifteen different herbicides were used in Vietnam between January 1965 and September 1971 by the US Air Force to kill unwanted plants and to remove leave from trees (Stellman et al., 2003). The amount of herbicide spayed per year increased over time and the most heavily sprayed areas included inland forests near the demarcation zone; inland forests around the borders of Cambodia, Laos and South Vietnam; inland forests north and northwest of Saigon; mangrove forests on the southernmost peninsula of Vietnam and mangrove forests along major shipping channels southeast of Saigon. Around 60% of the herbicide sprayed in Vietnam was *Agent Orange* (Young and Reggiani, 1988). This mix of chemicals contained equal amounts of two active ingredients (2,4-D and 2,4,5-T). This 'defoliation mission' affected over 2.61 million ha of land, of which more than 2 million ha was forest. Loss of foliage, flower and fruit occurred within 2–3 weeks of spraying (Buckingham, 1982) and some trees died. However, the majority of trees survived, but were damaged permanently. Agent Orange also caused a wide range of dysfunctions in humans, including prostate cancer, respiratory cancer, multiple myeloma and soft tissue sarcoma (NAS, 2003).

4.1.1. Data and data processing

The following data sets were used to derive current MTCI and surrogate (inverse) chlorophyll content at selected forest sites.

MERIS data: Two MERIS full resolution (300 m) images acquired on 8th June 2003 were used to produce a mosaic of southern Vietnam. These images were (i) geometrically corrected (using the ground control points provided by (ESA)), (ii) MTCI was calculated and (iii) non-forest areas were masked using a landcover map produced as a part of

Global Land Cover-2000 (GLC-2000) project (JRC, 2004). Only the forest area was used for further analysis (Fig. 3a).

HERBS files: The HERBS (HERBicide Spray) files contained information on the amount and extent of spraying missions (between August 1965 and December 1971) in southern Vietnam. The information included date of mission, amount of herbicide sprayed, types of herbicide and the start and end point of each flight path. These files were analysed in a GIS at a spatial resolution of 300 m and correlated with MTCI (above) images (Fig. 3b).

4.1.2. Initial results

Visual observations indicated that high herbicide concentrations in Fig. 4b (red) corresponded with low MTCI values in Fig. 4c (yellow). To study the relation between MTCI and herbicide concentration, random points were selected across the image. Strong negative relationships between the two were found ($r^2 > 0.73$).

Further investigation of the MTCI and herbicide concentration relationship is underway.

4.2. MTCI/chlorophyll content relationship in the New Forest and greenhouse

Vegetation spectra, vegetation amount and chlorophyll concentration are being collected at the New Forest study site and in a greenhouse; the latter under controlled conditions.

MTCI will be evaluated in terms of its sensitivity to variation in actual chlorophyll content at the two different scales.

5. Conclusion

The relation between REP and MTCI was strongly asymptotic and remained the same for model, field and MERIS data. The MTCI fulfilled the design criteria in that it was easy to calculate from MERIS data recorded at the standard band setting and was sensitive to a wide range of chlorophyll contents. Indirect evaluation revealed four characteristics that are relevant here:

1. There was only one MTCI value for each pixel (unlike REP value that will vary with method employed).
2. Calculation of the MTCI could be automated readily, as it involved one step and no manual intervention.
3. Should it be necessary REP can be estimated from MTCI, as a strong relationship exists between REP and MTCI.
4. MTCI was more sensitive than REP to high chlorophyll contents.

The MTCI appeared to be a most suitable index for the estimation of chlorophyll content with MERIS data. Further research to investigate the value of MTCI is now underway. This involves an evaluation of the MTCI/chlo-

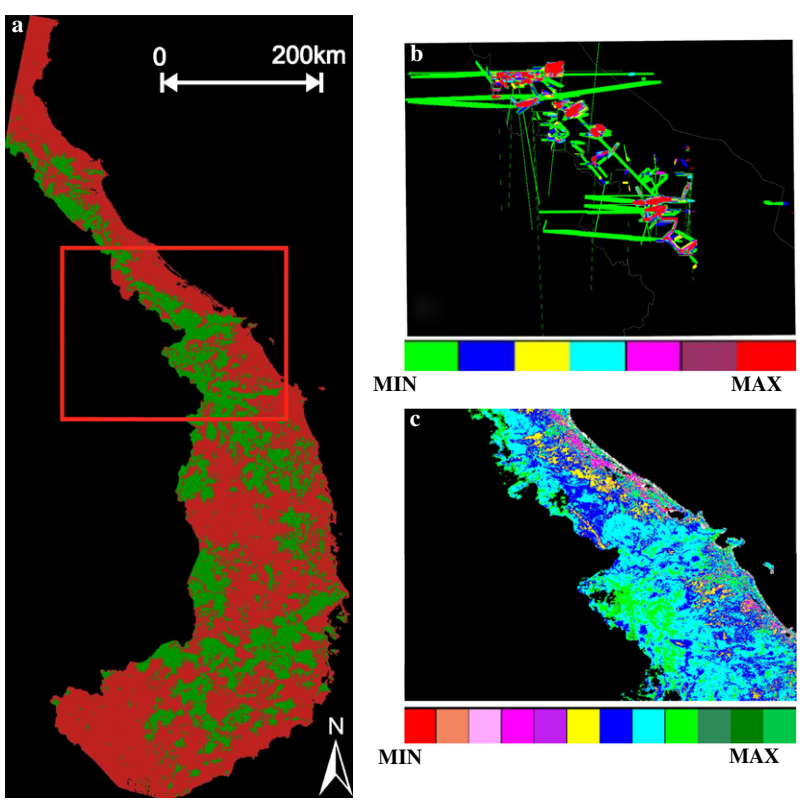

Fig. 3. (a) MERIS image of southern Vietnam (■ forest and ■ non-forest) with study area in red rectangle; (b) Agent Orange concentration image for the study area; (c) MTCI image for the study area. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this paper.)

rophyll content relationship using surrogate chlorophyll content data for southern Vietnam and actual chlorophyll content data in the greenhouse and field.

References

Buckingham, W.A. Operation Ranch Hand: The air force and herbicides in southeast Asia, 1961–1971. Office of Air Force History, United States Air Force, Washington, DC, 1982.

Clevers, J.G.P.W., De Jong, S.M., Epema, G.F., et al. Derivation of the red edge index using the MERIS standard band setting. International Journal of Remote Sensing 23, 3169–3184, 2002.

Curran, P.J., Dungan, J.L., Gholz, H.L. Exploring the relationship between reflectance red edge and chlorophyll content in slash pine. Tree Physiology 7, 33–48, 1990.

Dash, J., Curran, P.J. The MERIS terrestrial chlorophyll index. International Journal of Remote Sensing 25, 5003–5013, 2004.

Dawson, T.P., Curran, P.J. A new technique for interpolating the reflectance red edge position. International Journal of Remote Sensing 19, 2133–2139, 1998.

Dawson, T.P., Curran, P.J., Plummer, S.E. LIBERTY – modelling the effects of leaf biochemical concentration on reflectance spectra. Remote Sensing of Environment 65, 50–60, 1998.

Dawson, T.P. The potential of estimating chlorophyll content from a vegetation canopy using the Medium Resolution Imaging Spectrometer (MERIS). International Journal of Remote Sensing 21, 2043–2051, 2000.

Filella, I., Peñuelas, J. The red edge position and shape as indicators of plant chlorophyll content, biomass and hydric status. International Journal of Remote Sensing 15, 1459–1470, 1994.

Horler, D.N.H., Dockray, M., Barber, J. The red edge of plant leaf reflectance. International Journal of Remote Sensing 4, 273–288, 1983.

Jago, R.A., Cutler, M.E., Curran, P.J. Estimation of canopy chlorophyll concentration from field and airborne spectra. Remote Sensing of Environment 68, 217–224, 1999.

JRC, 2004. Available from: <http://www.gvm.sai.jrc.it/glc2000/defaultGLC2000.htm>.

Munden, R., Curran, P.J., Catt, J.A. The relationship between red edge and chlorophyll concentration in the Broadbalk winter wheat experiment at Rothamsted. International Journal of Remote Sensing 15, 705–709, 1994.

NAS, Characterizing exposure of veterans to Agent Orange and other herbicides used in Vietnam. Final Report, National Academy of Science, Washington, DC, 2003.

Rast, M., Bézy, J.L., Bruzzi, S. The ESA Medium Resolution Imaging Spectrometer (MERIS): a review of the instrument and its mission. International Journal of Remote Sensing 20, 1681–1702, 1999.

Stellman, J., Stellman, M., Christian, S.D., et al. The extent and patterns of usage of Agent Orange and other herbicides in Vietnam. Nature 422, 681–687, 2003.

Verhoef, W. Light scattering by leaf layers with application to canopy reflectance modelling: The SAIL model. Remote Sensing of Environment 16, 125–141, 1984.

Yoder, B., Johnson, L. Seedling canopy chemistry, 1992–1993 (ACCP) (Accelerated Canopy Chemistry Program). Dataset available on-line [http://www.daac.ornl.gov] from Oak Ridge National Laboratory Distributed Active Archive Center, Oak Ridge, Tennessee, 1999.

Young, A.L., Reggiani, G.M. Agent Orange and its Associated Dioxin: Assessment of a Controversy. Elsevier, Amsterdam, 1988.