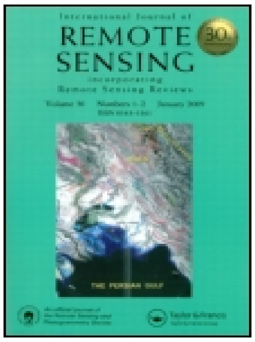

ISSN: 0143-1161 (Print) 1366-5901 (Online) Journal homepage: https://www.tandfonline.com/loi/tres20

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INT. J. REMOTE SENSING, 10 DECEMBER, 2004,
VOL. 25, NO. 23, 5403–5413

Taylor & Francis
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(*Received 16 June 2003; in final form 7 June 2004*)

Abstract. The long wavelength edge of the major chlorophyll absorption feature in the spectrum of a vegetation canopy moves to longer wavelengths with an increase in chlorophyll content. The position of this red-edge has been used successfully to estimate, by remote sensing, the chlorophyll content of vegetation canopies. Techniques used to estimate this red-edge position (REP) have been designed for use on small volumes of continuous spectral data rather than the large volumes of discontinuous spectral data recorded by contemporary satellite spectrometers. Also, each technique produces a different value of REP from the same spectral data and REP values are relatively insensitive to chlorophyll content at high values of chlorophyll content. This paper reports on the *design* and *indirect evaluation* of a surrogate REP index for use with spectral data recorded at the standard band settings of the Medium Resolution Imaging Spectrometer (MERIS). This index, termed the MERIS terrestrial chlorophyll index (MTCI), was evaluated using model spectra, field spectra and MERIS data. It was easy to calculate (and so can be automated), was correlated strongly with REP but unlike REP was sensitive to high values of chlorophyll content. As a result this index became an official MERIS level-2 product of the European Space Agency in March 2004. Further direct evaluation of the MTCI is proposed, using both greenhouse and field data.

1. Introduction

Remotely sensed data recorded in narrow visible/near visible wavebands can be used to estimate foliar biochemical content at local to regional scales (Curran 1989, Curran *et al*. 1997). This information can, in turn, be used to quantify, understand and manage vegetated environments (Johnson 1999, Curran 2001, Lamb *et al*. 2002). 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 space-borne sensor. First, the methods

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International Journal of Remote Sensing
ISSN 0143-1161 print/ISSN 1366-5901 online © 2004 Taylor & Francis Ltd
http://www.tandf.co.uk/journals
DOI: 10.1080/0143116042000274015

used to estimate REP have been designed for use on continuous spectra without thought for standardization 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 (Munden *et al*. 1994, Jago *et al*. 1999).

The Medium Resolution Imaging Spectrometer (MERIS), one of the payloads on the European Space Agency's Envisat, is radiometrically the most accurate imaging spectrometer in space (Curran and Steele 2004). It has 15 programmable (2.5–20 nm wide) wavebands in the 390–1040 nm region and a spatial resolution of 300 m. Because of its fine spectral and moderate spatial resolution and three-day repeat cycle, MERIS is a potentially valuable sensor for the measurement and monitoring of terrestrial environments at regional to global scales (Verstraete *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 nm, 681.25 nm, 708.75 nm, 753.75 nm and 760.625 nm. Two techniques have been used to estimate the REP on discontinuous (simulated) MERIS spectra: Lagrangian interpolation (Dawson 2000) and linear interpolation (Clevers *et al*. 2002).

1.1. *Lagrangian interpolation*

Dawson and Curran (1998) proposed a technique based on three-point Lagrangian interpolation (Jeffrey 1985) for the estimation of REP. This uses a second-order polynomial fit to the first derivative vegetation reflectance spectrum and reflectance in three wavebands: the band with maximum first derivative reflectance and two adjoining bands. REP is:

$$\mathrm{REP}=\frac{A(\lambda_i+\lambda_{i+1})+B(\lambda_{i-1}+\lambda_{i+1})+C(\lambda_{i-1}+\lambda_i)}{2(A+B+C)} \tag{1}$$

where, $A=\dfrac{D\lambda_{(i-1)}}{(\lambda_{i-1}-\lambda_i)(\lambda_{i-1}-\lambda_{i+1})}$ $B=\dfrac{D\lambda_{(i)}}{(\lambda_i-\lambda_{i-1})(\lambda_i-\lambda_{i+1})}$ $C=\dfrac{D\lambda_{(i+1)}}{(\lambda_{i+1}-\lambda_{i-1})(\lambda_{i+1}-\lambda_i)}$

In this case $D\lambda_{(i-1)}$, $D\lambda_{(i)}$, $D\lambda_{(i+1)}$ are the first derivative reflectances corresponding to wavebands $\lambda_{(i-1)}$, $\lambda_{(i)}$, $\lambda_{(i+1)}$ respectively ($\lambda_{(i)}$ is the band with maximum first derivative reflectance with $\lambda_{(i-1)}$ and $\lambda_{(i+1)}$ representing the bands either side of it).

The advantages of Lagrangian interpolation are: (i) wavebands used for the estimation of REP need not be spaced equally; (ii) the use of first derivative spectrum minimizes interpolation errors; and (iii) computationally it is one of the simpler curve-fitting techniques. Dawson (2000) showed that the Lagrangian interpolation technique could be used to detect a shift in the REP for simulated MERIS data in standard band positions. However, Clevers *et al*. (2002) reported a 'jumping' feature in a nonlinear REP/chlorophyll content relationship derived using Lagrangian interpolation. This was thought to be due to the 'not unusual' occurrence of more than one peak in the first derivative spectrum. Lagrangian interpolation, if used operationally, would therefore require manual confirmation of contented first derivative reflectance maxima, thus making it a semi-automatic two-step procedure.

1.2. *Linear interpolation*

Guyot *et al*. (1988) proposed a linear interpolation technique for estimating the REP. They assumed that reflectance at the red edge could be estimated by half of the reflectance between 670 nm and 780 nm. Reflectances at 670 nm and 780 nm were then used to calculate the reflectance of the inflection point and a linear interpolation technique was used to calculate the wavelength of this inflection point. So there are two steps: first, calculation of reflectance at the inflection point (equation (2)) and second, calculation of the REP (equation (3))

$$R_i = \frac{(R_{670} + R_{780})}{2} \tag{2}$$

where R_i is the reflectance at wavelength i;

$$\mathrm{REP} = 700 + 40\frac{(R_i - R_{700})}{(R_{740} - R_{700})} \tag{3}$$

The linear interpolation technique can be modified for MERIS data using wavebands 7 and 12 with centres at 665 nm and 778.75 nm. Equations (2) and (3) become

$$R_i(\mathrm{MERIS}) = \frac{(R_{\mathrm{Band7}} + R_{\mathrm{Band12}})}{2} = \frac{(R_{665} + R_{778.75})}{2} \tag{4}$$

where R_i(MERIS) is reflectance at the inflection point for MERIS data;

$$\begin{aligned}\mathrm{REP(MERIS)} &= 708.75 + 45\frac{(R_i(\mathrm{MERIS}) - R_{\mathrm{Band9}})}{(R_{\mathrm{Band10}} - R_{\mathrm{Band9}})}\\ &= 708.75 + 45\frac{(R_i(\mathrm{MERIS}) - R_{708.75})}{(R_{753.75} - R_{708.75})}\end{aligned} \tag{5}$$

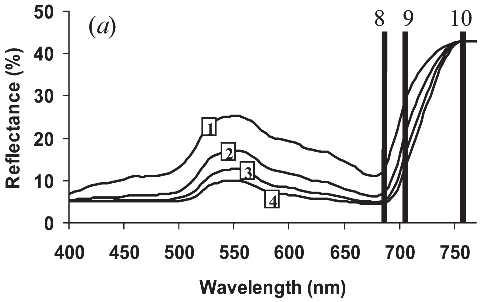
The linear interpolation technique is computationally simple and Clevers *et al.* (2002) reported it to be a robust method for estimating REP. However, a correction needs to be made to allow for the occurrence of an oxygen absorption band near 753.75 nm (one of the wavebands used in interpolation).

Undoubtedly, other REP techniques will be applied to MERIS data for the estimation of chlorophyll content. However, (i) there remains no generally accepted technique for estimation of REP, (ii) each technique produces a different value of REP from the same set of data, and (iii) neither of the techniques reviewed above offers the automated, one-step procedure that would be required for the processing of large volume data at, for example, a ground receiving station. In this paper a new index for estimating chlorophyll content from MERIS data has been designed as a surrogate for REP.

2. Designing a 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) are given in figure 1(*a*), 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 (figure 1(*a*)). 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



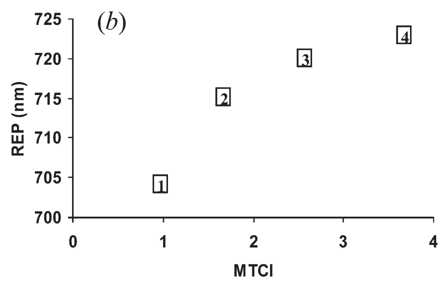


Figure 1. (*a*) Illustrative vegetation reflectance spectra at four chlorophyll contents (model output) overlain with the position of MERIS bands 8, 9 and 10. (*b*) Relation between the MERIS terrestrial chlorophyll index (MTCI) and red-edge position (REP) for four chlorophyll contents.

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.

$$\begin{aligned}\text{MTCI} &= \frac{R_{\text{Band10}} - R_{\text{Band9}}}{R_{\text{Band9}} - R_{\text{Band8}}} \\ &= \frac{R_{753.75} - R_{708.75}}{R_{708.75} - R_{681.25}}\end{aligned} \tag{6}$$

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

Figure 1(*b*) illustrates the relation between MTCI and REP for the four illustrative spectra in figure 1(*a*). The REP calculated using linear interpolation is illustrated here because of its simplicity; however, REP calculated using Lagrangian interpolation provided similar, albeit linearly offset, results. It can be seen that there is little change in REP but a large change in MTCI between high chlorophyll contents. This implies that MTCI is more sensitive to change in chlorophyll content at high chlorophyll contents than is REP.

The logistical difficulty of obtaining accurate chlorophyll content assays for many (>25) suitably sized ($>10^5\,\text{m}^2$) plots of land effectively prevents a direct assessment of the MTCI. Therefore, an indirect approach was used.

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. Indirect MTCI evaluation methods

3.1. *Model data*

LIBSAIL, a combination of LIBERTY (Leaf Incorporating Biochemistry Exhibiting Reflectance and Transmittance Yield (Dawson *et al.* 1998)) and SAIL (Scattering by Arbitrary Inclined Leaves (Verhoef 1984)) was used to generate canopy reflectance spectra (400–2500 nm, spectral resolution of 5 nm) for a wide range of chlorophyll contents. The variables input to the combined model are given in table 1.

Table 1. Input variables for LIBSAIL model.

LIBSAIL variables	Values
Chlorophyll content ($mg\,m^{-2}$)	10, 20, 50, 100, 150, 200, 250, 300, 350, 400
Average internal cell diameter (μm)	30
Intercellular airspace determinant (unitless)	0.005
Leaf thickness (unitless)	3
Base line absorption (unitless)	0.0004
Albino leaf absorption (unitless)	2
Leaf water content ($g\,m^{-2}$)	100
Lignin or cellulose content ($g\,m^{-2}$)	30
Nitrogen content ($g\,m^{-2}$)	1
Solar zenith angle (°)	0.0
Mean leaf inclination (°)	30
Leaf area index	1

3.2. *Field data*

Canopy reflectance spectra and canopy chlorophyll content data had been collected for monospecific canopies formed from Douglas fir (*Pseudotsuga menziesii*) and bigleaf maple (*Acer macrophyllum*) seedlings as a part of NASA's 1992–1993 Accelerated Canopy Chemistry Program (ACCP) (Yoder and Johnson 1999).

Model and field reflectance data were averaged according to the band centre and band width of the MERIS standard bands to obtain the reflectance data used to calculatate the REP (equation (5)) and MTCI (equation (6)).

3.3. *MERIS data*

A subset of a MERIS image acquired on 19 October 2002 was extracted for the New Forest, Hampshire, UK. The area comprises coniferous and deciduous woodland along with heath, meadows, agricultural land, urban areas and water. The data were atmospherically corrected and converted to top-of-canopy reflectance using the simplified methods for atmospheric correction (SMAC) (Rahman and Dedieu 1994). For illustrative purposes a false colour composite was generated using band 10 data as red, band 8 data as green and band 6 data as blue (figure 5(*b*)) and the data were classified using an unsupervised algorithm (Isodata) (figure 5(*c*)).

4. Indirect MTCI evaluation results

4.1. *Model data*

Vegetation reflectance obtained from LIBSAIL spectra for simulated MERIS band positions over a wide range of chlorophyll contents ($10\,mg\,m^{-2}$ to $400\,mg\,m^{-2}$) are shown in figure 2(*a*). An increase in chlorophyll content was associated with increased absorption in red wavelengths but the amount of absorption was less at high chlorophyll contents than at low chlorophyll contents. Estimated MTCI and REP for each spectrum are given in figure 2(*b*) and 2(*c*) respectively.

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

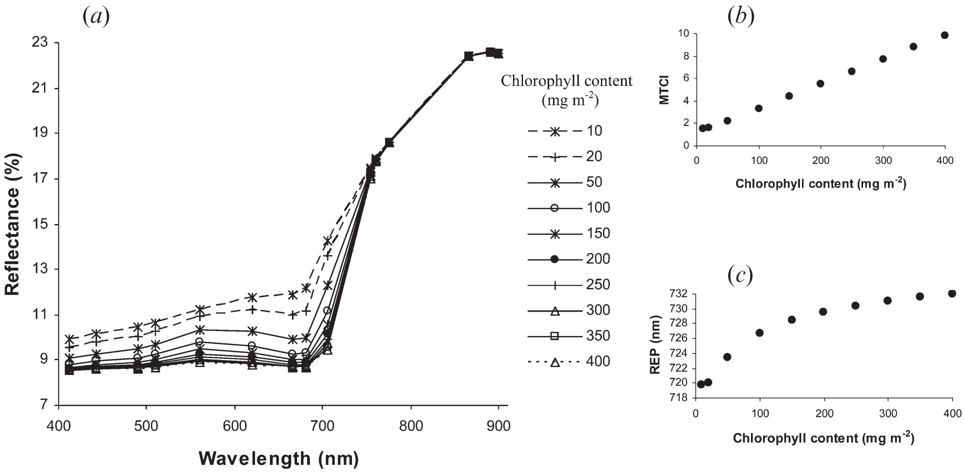


Figure 2. (*a*) Reflectance spectra for MERIS data at the standard band settings, simulated using the LIBSAIL model for a wide range of chlorophyll contents; (*b*) relation between chlorophyll content and MTCI for the same range of chlorophyll contents; and (*c*) relation between REP and chlorophyll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

4.2. *Field data*

For Douglas fir (figure 3(*a*)), the coefficients of determination (r^2) were 0.64 and 0.62 between chlorophyll content and first MTCI and second REP. Similarly, for maple (figure 3(*b*)) the coefficients of determination (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.

The relationship between REP and MTCI was determined using both continuous (2 nm spacing between bands) reflectance spectra and reflectance at the MERIS standard band settings (figure 4). REP and MTCI were correlated strongly (r^2 greater than 0.99 and 0.98 for Douglas fir and maple respectively) for values derived using both continuous reflectance spectra and reflectance at the MERIS standard band settings. However, reflectance at the MERIS standard band settings resulted in higher values of REP (Dawson 2000) because of the large spectral interval between the MERIS bands 9 and 10 (centres located at 705 nm and 753.75 nm). Interestingly, the relationship between REP and chlorophyll content and MTCI and chlorophyll content was almost the same for the two species, suggesting little species-to-species variation in these relationships.

4.3. *MERIS data*

Analysis of the MERIS data is presented in two forms: first, images of NDVI (for convenience and ease of interpretation), REP and MTCI (figure 5, table 2); and second, graphs of relations between NDVI, REP and MTCI for both heath and woodland. The NDVI image (figure 5(*d*)) delineated three broad zones: (i) vegetated with high NDVI (and assumed high chlorophyll content) in woodland areas near the image centre; (ii) vegetated with intermediate NDVI (and assumed lower

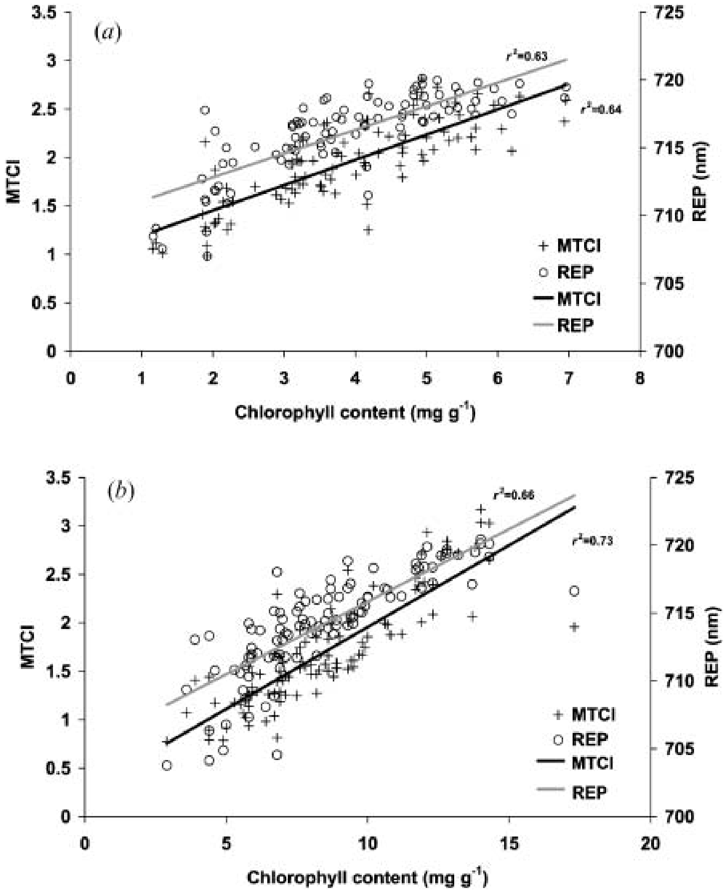


Figure 3. Sensitivity of REP and MTCI calculated from field reflectance spectra to variation in chlorophyll content for (*a*) Douglas fir and (*b*) maple.

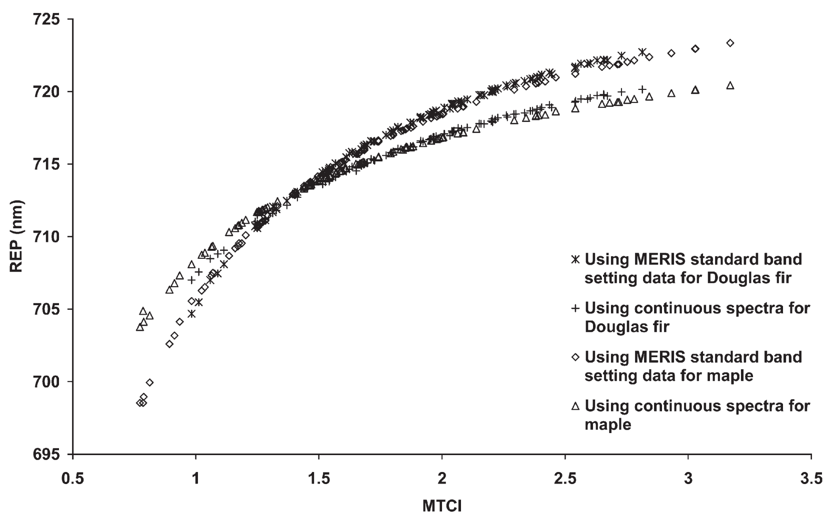


Figure 4. Relation between REP and MTCI, estimated using continuous spectra and MERIS standard band settings for field reflectance data of Douglas fir and maple.

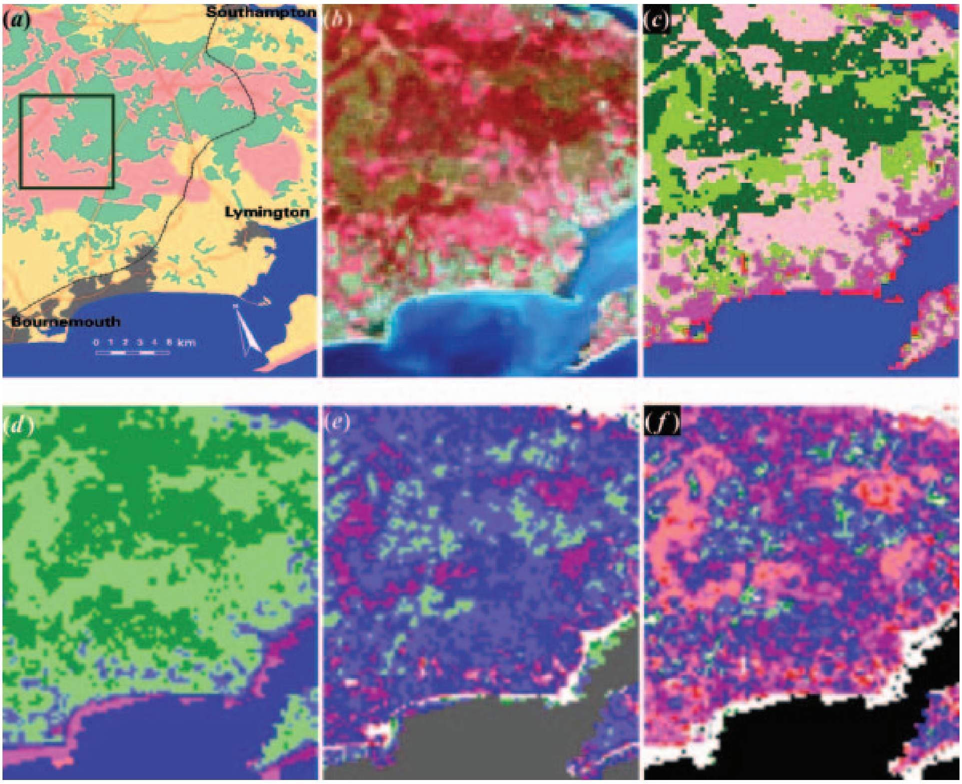


Figure 5. MERIS images of southern England: (*a*) land cover map of the study area (New Forest) with the black box indicating the subscene (6.3 km × 6.3 km) containing vegetation with the assumed relatively high and low chlorophyll content that was selected for quantitative analysis; (key: heath, woodland, meadows and agricultural land, urban, water); (*b*) false colour composite image of bands 10, 8 and 6; (*c*) classified (unsupervised) image; (*d*) NDVI image, colour key in table 2; (*e*) REP image, colour key in table 2; and (*f*) MTCI image, colour key in table 2.

chlorophyll content) in heath, meadows and agricultural land towards, for example, the western edge of the image; and (iii) non-vegetated with, for example, low or negative NDVI values in urban and coastal areas. The REP image (figure 5(*e*))

Table 2. Key for NDVI, REP and MTCI images in figure 5.

	NDVI		REP		MTCI	
Colour	min.	max.	min.	max.	min.	max.
	−0.4	−0.2370	705	707.37	1	1.2
	−0.2371	−0.0740	707.38	709.75	1.21	1.4
	−0.0741	0.0890	709.76	712.12	1.41	1.6
	0.0891	0.2520	712.13	714.5	1.61	1.8
	0.2521	0.4149	714.51	716.87	1.81	2.0
	0.4150	0.5779	716.88	719.25	2.01	2.2
	0.5780	0.7409	719.26	721.62	2.21	2.4
	0.7410	0.9039	721.63	724	2.41	2.6

identified some variation within these broad NDVI zones; however, the MTCI image (figure 5(*f*)) 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.

Relationships between NDVI, REP and MTCI were illustrated (figure 6) for a 6.3 km × 6.3 km image subscene (figure 5(*a*)) comprising heath and woodland. For heath (assumed relatively low chlorophyll content) there was a near-linear

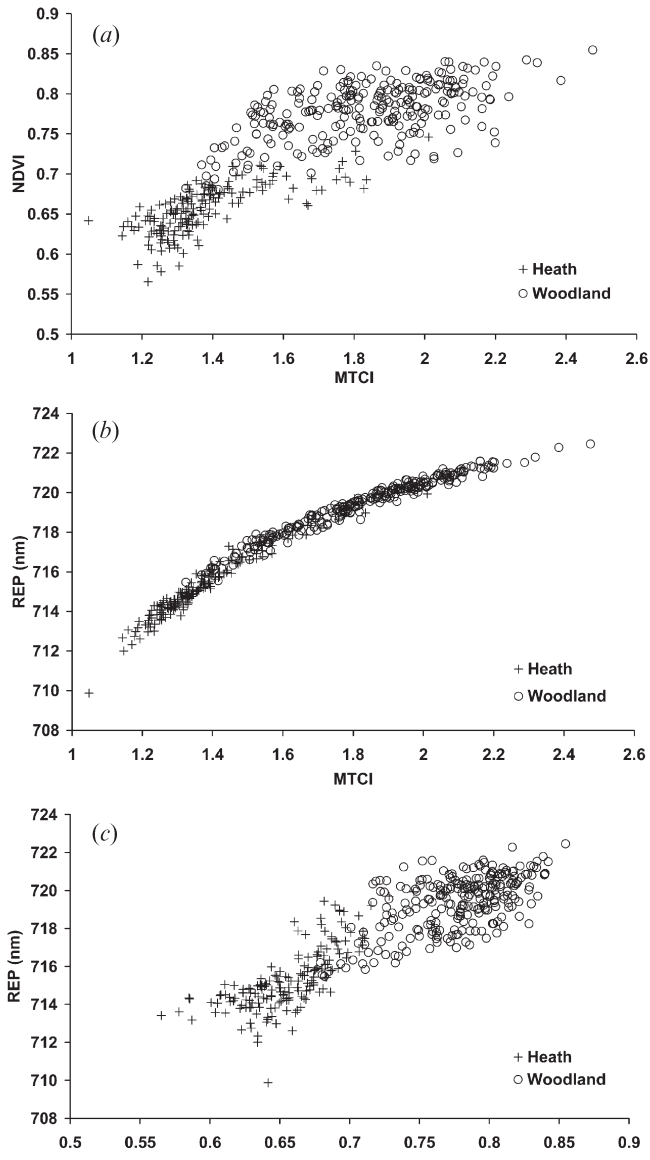


Figure 6. Relationships between (*a*) NDVI and MTCI, (*b*) REP and MTCI, and (*c*) REP and NDVI for a subscene of MERIS data (figure 5(*a*)) containing heath and woodland.

relationship between NDVI and MTCI, but for woodland areas (assumed high chlorophyll content) there was little change in NDVI with change in MTCI (figure 6(*a*)). The relationship between REP and MTCI (figure 6(*b*)) was strong and little influenced by the assumed chlorophyll content. As the NDVI had an asymptotic relationship with MTCI in figure 6(*a*), so the REP was shown to have an asymptotic relationship with NDVI in figure 6(*c*). Together the three graphs in figure 6 point to the value of MTCI as a surrogate for REP that is sensitive to variability in chlorophyll content over a wide range of chlorophyll contents.

5. Direct MTCI evaluation

To investigate directly the relationship between MTCI and chlorophyll content field measurements of spectra, vegetation amount and chlorophyll concentration will be made at the New Forest study site and in a greenhouse under controlled conditions.

The three measures (MTCI, REP and NDVI) will be evaluated directly in terms of their sensitivity to variation in chlorophyll content at a regional scale (for MERIS data), at a local scale (for field data) and at a canopy scale (for greenhouse data).

6. Discussion and conclusion

Indirect evaluation indicated that 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 (§2) 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 (MTCI is an absolute value derived using a specific method, unlike the REP which is a method specific estimate of an actual value).
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. As a result the MTCI became an official MERIS level 2 product of the European Space Agency in March 2004. Further research to investigate the value of MTCI is now underway. This involves a direct evaluation of the MTCI/chlorophyll content relationship using field and greenhouse data.

Acknowledgment

The authors wish to thank Oak Ridge National Laboratory (ORNL) Distributed Active Archive Center (DAAC) for ACCP data, the European Space Agency for MERIS data (as a part of a Principal Investigatorship) and Gary Llewellyn, Ajay Mathur and Dr Caiti Steele (University of Southampton) for assistance and advice.

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