Remote estimation of chlorophyll concentration in productive waters: Principals, algorithm development and validation

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Abstract

Most of the information pertaining to remote sensing of phytoplankton was developed for oligotrophic waters, where detritus and inorganic particles are scarce or their concentrations correlate with phytoplankton density. In our study we concentrated on inland and productive coastal waters, with the initial work done in Lake Kinneret, Israel. The primary objectives were: (1) to study the spectral features of reflectance of different water bodies during different seasons of the year, in order to find spectral features which are closely related to phytoplankton density; and, (2) to devise and validate algorithms for chlorophyll estimation using reflectance data as the measured variables. We found that the information gained from several spectral bands in the red and near-infra-red ranges of the spectrum were sufficient for the construction of algorithms for phytoplankton density estimation. These algorithms were validated in Lake Kinneret, as well as in other environments, with slight modification of the coefficients: the polluted water of Haifa Bay (Mediterranean Sea), fish ponds and wastewater reservoirs in Israel, and lakes with diverse trophic status in northwestern Iowa and eastern Nebraska (USA). Within the context of information essential for the estimation of chlorophyll concentration by remotely operated instruments, we discuss the requirements for satellite sensors to make them expedient tools for monitoring quality of productive aquatic ecosystems.

Introduction

The patchy nature of phytoplankton distribution is a challenge to any survey effort on larger water bodies. Therefore, remote sensing techniques, which offer a synoptic view of most or all the surface zones of water bodies in question, are a promising solution. The initial efforts to use remote sensing for phytoplankton monitoring were done in marine pelagic environments, where phytoplankton is often a dominant component of the suspended matter, and the total concentration of chlorophyll *a* (Chl), a signature substance of phytoplankton is mostly below 1 mg/m^3 (Morel and Prieur, 1977; Gordon and Morel, 1983; Kirk, 1994, Bukata *et al.* 1995). Most inland waters are classified as Case II waters (Morel and Prieur, 1977); in productive waters, the Chl concentration is often moderate to high and phytoplankton concentration is not tightly coupled to the density of total seston.

Chl concentrations in Lake Kinneret, Israel, range from less than 5 mg/m^3 to hundreds of mg/m^3 (Berman *et al.* 1992). The spatial distribution of Lake Kinneret phytoplankton is very heterogeneous, particularly when the dinoflagellate *Peridinium gatunense* in almost all years forms a dense bloom from February through May (Pollingher, 1986; Berman, *et al.* 1995). Funding considerations limit the sampling schedule to a few stations, and routinely to a single station, located above the deepest point of the lake. It is questionable whether this single station (or even a few stations) is truly representative the overall condition. To overcome this problem, we have initiated a program for remote sensing of chlorophyll in Lake Kinneret in October 1992. The primary aims were (1) to study the characteristics of the reflectance spectra during different seasons of the year, (2) to evaluate concepts developed for estimation of Chl concentration in inland waters (Gitelson, 1986, 1993a,b), and (3) to devise algorithms for Chl estimation in Lake Kinneret from reflectance data. Following the establishment of algorithms for Chl detection in Lake Kinneret, an effort was undertaken to assess their validity in other productive and turbid water bodies in Israel and in the USA. In this paper, we present the summary of our work in those diverse water bodies, where remotely sensed data were used for the estimation of Chl concentrations.

Materials and Methods

Data were collected in several locations in Israel and in the north central United States. A list of water bodies examined is given in Table 1. Descriptions of optical properties of these water bodies have been published previously: Lake Kinneret (Gitelson *et al.* 1994a,b; Yacobi *et al.* 1995), Haifa Bay (Gitelson *et al.* 1996), Carter Lake (Schalles *et al.* 1998), northwestern Iowa lakes (Jones & Bachman, 1974), and wastewater treatment ponds (Oron and Gitelson, 1996; Stark *et al.* 1996; Gitelson *et al.* 1997). In each experiment, upwelling radiance of water (L_w) and reference plate (L_{ref}) were measured using high spectral resolution spectroradiometers: LI-1800 (aquatic systems in Israel), Ocean Optics ST1000 (Carter Lake), and ASD (Iowa lakes). Reflectance spectra were then calculated as $R = L_w/L_{ref}$. Water samples were collected for analytical determination of Chl *a* concentration in the laboratory. Detailed descriptions of the analytical methods and data processing used for the treatment of the measured variables were presented in the mentioned above publications.

Table 1. Water bodies studied, period of observations, range of chlorophyll variation and dominant phytoplankton.

Site	Period	Chlorophyll *a* (mg/m^3)	Dominant phytoplankton
Lake Kinneret	winter-spring	2.4 - 330	Peridinium gatunense
Lake Kinneret	summer-fall	3.8 - 26	chlorophytes
Iowa Lakes, USA	summer	2.0 - 55	diatoms
Carter Lake, USA	year round	20 - 280	Anabaena sp.
Fish ponds, northern Israel	winter-spring	2.1 - 674	Microcystis aeruginosa
Wastewater ponds, Israel	spring-summer	69 -2700	chlorophytes
Haifa Bay, Israel	spring-summer	1 - 70	dinoflagellates, diatoms

Results and Discussion

Reflectance spectra

Upwelling radiance of water harbors information on the concentrations and composition of dissolved and suspended substances in the water, and is "the raw material" for remote estimation of concentrations of water constituents. Here we focused on spectral features determined by chlorophyll *a* absorbance and scattering by phytoplankton cells. All water constituents have significant optical activity in spectral range 400 to 500 nm. It includes absorption by dissolved organic matter and scattering by particular matter, those decrease toward longer wavelengths, and absorption by chlorophylls and carotenoids (e.g., Kirk, 1994). Of special importance is a reflectance minimum near 440 nm (Figs. 1a and 2b), caused by Chl absorption; this feature is used in oligothrophic waters, in a reflectance (R) ratio at 440 nm and 550 nm (R_{440}/R_{550}), to estimate Chl concentration (Gordon and Morel, 1983). The minimum near 440 nm is often indistinct in reflectance spectra of productive waters, due to strong absorption by dissolved organic matter and scattering by particulate matter (Figs. 1b and 2a). In such waters, the reflectance near 440 nm becomes less sensitive (if any) to Chl concentration (Gitelson *et al*, 1994a; Rundquist *et al*. 1995; Schalles *et al*. 1997). In the range near 490 nm another trough of reflectance is seen (Fig. 1a and 2b), caused by carotenoids absorption (Gitelson *et al*. 1995; Yacobi *et al*. 1995). In the case of *Anabaena* the most abundant of this substances of this group were zeaxanthin, myxoxanthophyll, ochinenone and β-carotene (Schalles *et al*. 1998). In productive waters, as in Haifa Bay (Fig. 1a), Iowa lakes (Fig. 1b), lake Kinneret during Peridinium period (Fig. 2a) and fish ponds (Fig. 2b), reflectance in the range 400 to 500 nm became low with no pronounced spectral features within a broad range of total seston and phytoplankton densities. Thus, all optically active constituents (dissolved and suspended materials) contribute to reflectance in the range 400 to 500 nm, and a common characteristic of reflectance spectra in this range is low sensitivity of reflectance to phytoplankton density. Absorption by pigments is masked by absorption of dissolved organic matter and scattering by suspended matter.

In the range 500 nm to near infra-red (NIR), the reflectance showed several distinct features: (a) a peak in the green range near 550-570 nm, (b) a trough near 625 nm, (c) a trough at 670-680 nm, and (d) a distinctive peak in the red - NIR boundary near 700 nm.

A prominent peak of reflectance in the green range represents the minimal absorption of all algal pigments. Scattering by non-organic suspended matter and phytoplankton cell walls are factors, governing magnitude of reflectance in the green range (550 to 570 nm). Increase in concentration of particulate matter leads to increase in scattering and reflectance as well. Exceptions were Haifa Bay (Fig. 1a) and Lake Kinneret during Peridinium bloom (Fig. 2a), where non-organic suspended matter load was very low (phytoplankton was responsible for more than 90 percent of dry weight), and phytoplankton was the only constituent determined optical properties of water. Increase in phytoplankton density led to increase of scattering by phytoplankton cells and pigment absorption. Latter one was so strong that reflectance decreased, even scattering by phytoplankton cell increased. This decrease in reflectance appeared not only in the blue range but also in the green at wavelength located far away from main absorption bands of chlorophylls and carotenoids. It was caused by strong absorption by carotenoids, mainly those harbored by dinoflagellates, i.e., peridinin and diadinoxanthin. The position of the peak was dependent on carotenoid concentration as it was found in Haifa Bay (Fig. 1a) and in Carter Lake (Schalles *et al*. 1998). With increase in carotenoid concentration, absorption increased and manifestation of it was decrease in reflectance and shift of the peak position toward longer wavelength (from 550 to 570 nm, Fig. 1a). In Lake Kinneret during Peridinium bloom, absorption by carotenoids was so strong, that peak position was found at 570 even for Chl concentration as low as 5-15 mg/m^3 (Fig. 2a).

In waters dominated by blue-green algae in the range of 620-630 nm, a decline of reflectance is noticed (Figs. 2b, and 3), caused by the absorption of the cyanobacteria phycobillins (Dekker, 1993; Gitelson *et al*., 1995b). The depth of this feature varied seasonally, in accordance with cyanobacter abundance and seasonality (Fig. 3, see also Schalles *et al*. 1998). Increase in phycocyanin concentration led to increase in depth of the trough and, as a result, to shift of green peak position toward shorter wavelength (Fig. 3). Thus, in waters with blue-green algae, green peak position depends upon at least two factors: carotenoid and phycocyanin concentrations.
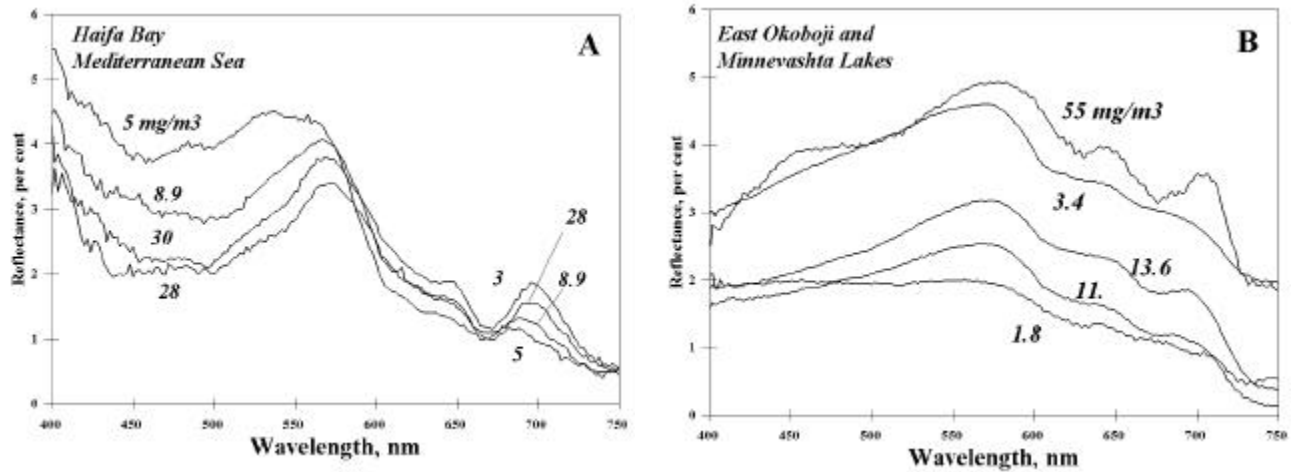
Fig. 1: Reflectance spectra of aquatic systems with low to moderate Chl concentrations.
(a) Haifa Bay, June 1995. With increase in Chl concentration to 20 mg/m^3, reflectance in the range 400 to 550 nm decreased; for Chl > 20 mg/m^3, the sensitivity of reflectance to Chl dropped significantly. In the range near 700 nm, reflectance was sensitive to Chl in a wide range of its variation.
(b) Lakes in northwestern Iowa, USA, June 1996. Peak near 700 nm was found to be the only spectral feature sensitive to Chl concentration.
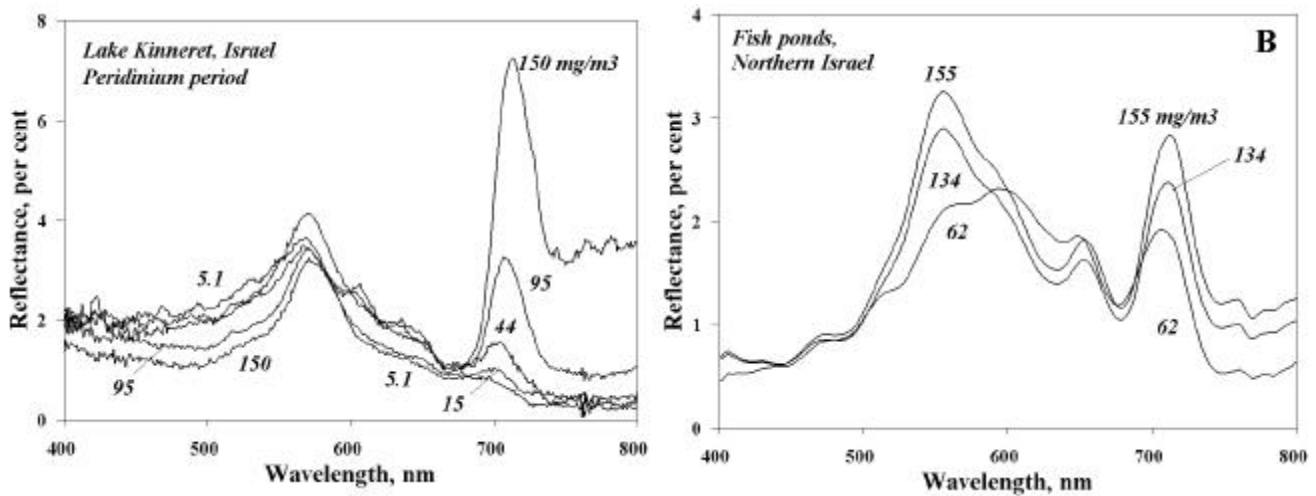

Fig. 2: Reflectance spectra of aquatic systems with moderate to high Chl concentrations.
(a) Lake Kinneret, February 1994. In the range 400 to 550 nm, absorption by pigments was so strong that it was hardly to distinguish between spectra with Chl ranged between 5 and 150 mg/m^3. Magnitude and position of the NIR peak depend strongly upon Chl concentration.
(b) Fishponds in the Jordan Valley, Israel, February 1998. Blue green algae were dominant in the ponds; thus, specific spectral feature of this algae can be seen as a gap near 625 nm.

The trough near 670 nm is due to maximum absorbance by chlorophyll *a* in the red range of the spectrum. For a Chl concentration of more than 20 mg/m^3, the reflectance at 670 nm (R_{670}) almost does not depend upon Chl (Fig. 2a) and primarily depends on concentration of non-organic suspended matter (Gitelson *et al.*, 1993a,b; Dekker, 1993; Gitelson *et al.*, 1994b; Yacobi *et al.*, 1995). At this point, chlorophyll absorbance is offset by scattering of the cell walls and is a point of minimum sensitivity of reflectance to algal density and Chl concentration.

In waters with low Chl concentrations, a peak of solar-induced Chl fluorescence was observed in reflectance spectra near 685 nm (Figs. 1a and b). With increase in Chl concentration, emitted fluorescence increased as well as the magnitude of the peak. The peak was used as an indicator of Chl concentration (e.g., Neville and Gower, 1977; Gower, 1980; Doerffer, 1981; Fischer & Kronfeld, 1990; GKSS, 1986).

With increase in Chl concentration above 15-20 mg/m^3, re-absorption of fluorescence signal occurs and magnitude of fluorescence peak decreases (Kishino et al. 1986; Gitelson, 1992; 1993), and the nature of the peak is very different from that for low Chl concentration (Gitelson *et al.*, 1986; Vos *et al.*, 1986; Gitelson 1992; 1993; Gitelson *et al.*, 1993a,b). This peak is an outcome of an interaction between strong absorption by chlorophyll and water and scattering by algal cells and other sestonic matter (Gitelson *et al.*, 1986; Vos *et al.*, 1986; Gitelson, 1992; 1993).
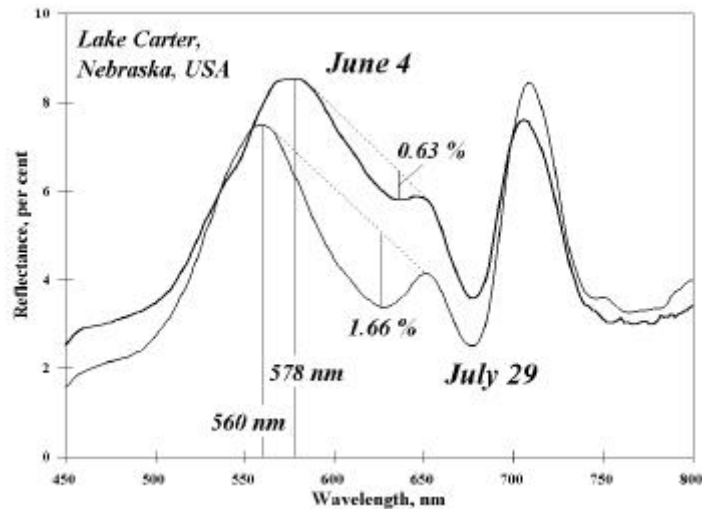

Fig. 3: Demonstration of accessory pigment effects on reflectance spectra. Two representative spectra from Carter Lake for June 4 and July 29, 1996. Chl concentrations were almost the same, but on July 29, phycocyanin (PC) concentration was much higher. As a result of higher PC concentration, the depth of a trough near 625 nm was at least twice more than that on June 4. The spectrum taken in July 29 shows a shifted position of the "green" peak towards shorter wavelengths.

The magnitude of the peak, as well as its position, depends strongly on Chl concentration (Gitelson 1992; 1993; Gitelson *et al.* 1994a; Yacobi *et al.* 1995, Schalles *et al.* 1998). The peak magnitude depends on scattering by all suspended matter and, thus, increases with increase in phytoplankton biomass. It correlated with Chl concentration *via* the link between Chl and algal biomass. As the algal biomass increases, or actually the active cell surface, scattering and the reflectance increase. In this range of the spectrum, combined absorption by Chl and water is minimal; therefore, the scattering surplus to the basic scattering by non-organic suspended matter may be attributed to phytoplankton cells surface (Gitelson *et al.* 1994a; Yacobi *et al.* 1995).

Chl has low but significant absorption between 690 and 715 nm. With increasing Chl concentration, the pigment absorption offsets cell scattering at progressively higher wavelengths, and the position of the peak shifts toward longer wavelengths (Figs. 2a,b, see also Gitelson *et al.*, 1986; 1993a,b; Vos *et al.*, 1986; Gitelson 1992; Rundquist *et al.*, 1995; Yacobi *et al.*, 1995, Schalles *et al.* 1998).

It is worth to note, that the distinctive spectral features of reflectance (Fig. 2a) characterized *Peridinium* bloom in Lake Kinneret. These reflectance spectra were conspicuously different from that observed in other seasons (reflectance spectra of the lake in non-Peridinium period resemble spectra obtained in Okoboji lakes, Fig. 1a, and in Haifa Bay, Fig. 1a, with Chl < 10 mg/m^3; see also Gitelson *et al.* 1994b). Thus, even for single lake, different approaches have to be used to estimate remotely Chl concentrations in different seasons.

Algorithm development and validation

<u>Low Chl concentration</u>. In productive, turbid waters with Chl concentration below 20 mg/m^3, the peak of Chl fluorescence near 685 nm was found to be the best spectral reflectance feature for estimating of Chl concentration. The height of the peak above a base line between 650 and 730 nm was used successfully for remote detection of Chl in Case II waters (e.g., Neville and Gower, 1977; Gower, 1980; Doerffer, 1981; Fischer & Kronfeld, 1990; GKSS, 1986). We slightly modified this algorithm placing the base line between 670 and 730 nm. It increased in certain degree the sensitivity of Chl detection (Gitelson *et al.* 1994b, Mayo *et al.*, 1995).

The quantitative accuracy of the technique is limited by the varying fluorescence efficiency of different phytoplankton populations and by changes in water constituent absorption and scattering that reduces the light available for excitation of fluorescence. This technique was found to be useful for Chl detection, however, it is difficult to generalize and make comparisons based on previous studies, especially for inland waters with highly variable bio-optical properties. Nevertheless, the technique proved expedient in Lake Kinneret during non-Peridinium period when Chl concentration were below 10 mg/m^3 (Gitelson *et al*. 1994b) and in Iowa lakes (Fig. 7a). In lake Kinneret, an estimation error of Chl, ranged from 3.8 to 16, was less than 1 mg/m^3; in Iowa lakes in the range of Chl concentration from 2 to 55 mg/m^3, an estimation error of 7.8 mg/m^3 was achieved.
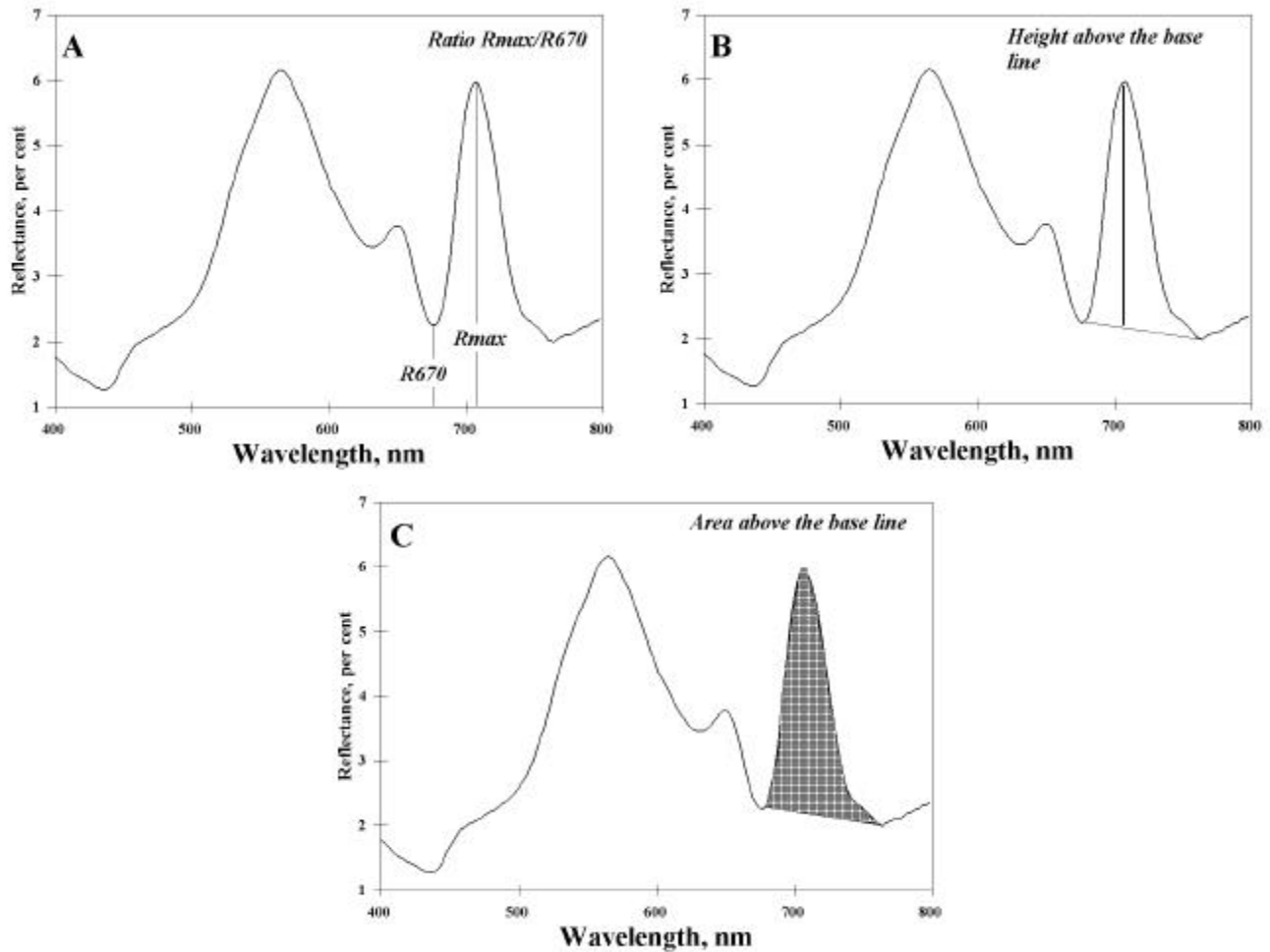

Fig. 4: Algorithms for estimation of Chl concentration. (a) Ratio of the peak magnitude to reflectance at 670 nm; (b) Reflectance height above the base line between 670 and 750 nm; (c) Area above the base line between 670 and 750 nm.

Moderate to high Chl concentration. The semi-analytical algorithms developed and tested in our work are all based on the use of reflectance in the red and NIR range of the spectrum, since other portions of the spectrum are irrelevant in productive, coastal and freshwater ecosystems (Gitelson *et al*. 1986; Vos *et al*. 1986; Gitelson, 1992; Mittenzwey and Gitelson, 1988; Mittenzwey *et al*. 1992; Millie *et al*. 1992; Quibell, 1992; Dekker 1993; Gitelson *et al*. 1993a,b; 1994a; Goodin *et al*. 1993; Boxall & Mathews, 1994; Han *et al*. 1994; Richardson *et al*. 1995; Rundquist *et al*. 1995, 1996; Yacobi *et al*. 1995; Schalles *et al*. 1997, 1998). The basic concept of those algorithms is the inclusion of the spectrum range which shows the maximal sensitivity to changes in Chl concentration and the range with the minimum sensitivity to variation of Chl concentration (Gitelson *et al*. 1986; 1993a,b; 1994a; Yacobi *et al*. 1995). The latter accounts for non-pigmented suspended matter that causes variation in the reflectance. Magnitude and position of the reflectance peak near 700 nm were found to be the most sensitive variable for algorithms, and the reflectance at 670 nm was the least sensitive to changes in algal density, especially for Chl > 15-20 mg/m^3.

A simple reflectance ratio R_{700}/R_{670} was first used as a predictor of Chl concentration (Gitelson *et al.* 1986; Mittenzwey & Gitelson, 1988; Mittenzwey *et al.* 1992; Gitelson *et al.* 1993a,b). The R_{700}/R_{670} ratio (Fig. 4a) was applied to our data obtained in highly diverse aquatic ecosystems dominated by different algal assemblages: Anabaena sp. (Fig. 5a), Micricystis aeruginosa (Fig. 5b), and Peridinium gatunense (Fig. 6). The relationship between the R_{700}/R_{670} ratio and Chl concentration was linear up to concentrations of approximately 180-200 mg/m^3, but turned exponential at higher concentrations (fig. 5b). To estimate accuracy of Chl prediction in lake Kinneret during Peridinium bloom, the combined dataset (reflectance spectra and Chl concentrations) was separated into model-development and model-testing subsets. For the model-development subset, data collected in March 1993 were used (Fig. 6). Validation was done by data, collected in April 1993. Predicted Chl concentrations were calculated using reflectance from model-testing subset with regression coefficients for the model-development dataset equation (solid line in Fig. 6). The accuracy of Chl prediction was made against Chl concentrations actually measured. Root-mean square deviation of predicted Chl values from actually measured did not exceed 18 mg/m^3 (insert in Fig. 6).
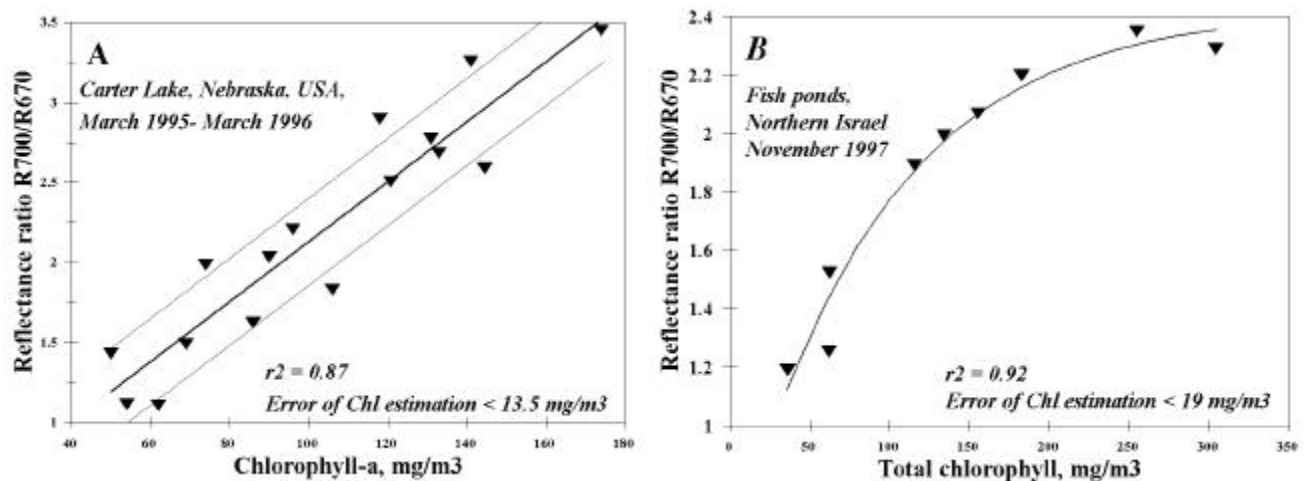

Fig. 5: Validation of the reflectance ratio algorithm, R700/R670, for estimation of Chl concentration.
(a) Carter Lake, March 1995-March 1996. The solid line represents best-fit function; the dotted lines represent standard error of chlorophyll estimation; (b) Fishponds in the Jordan Valley, Israel, February 1998. For Chl < 180 mg/m^3, the relationship ratio vs. Chl was linear, and then leveled off.

Several algorithms were developed for estimation of Chl concentration. They were based on the following variables: (a) the magnitude of the peak near 700 nm; (b) the height of the peak near 700 nm above the baseline drawn from 670 to 750 nm (Fig. 4b); (c) the area delimited by the reflectance curve and the mentioned baseline (Fig. 4c); (d) the position of the peak in NIR range. These algorithms were based on following concept. The trough at 670 nm is the wavelength of maximum absorbance by Chl in the red range of the spectrum. At this wavelength, Chl absorbance and scattering by cell walls are almost in equilibrium, and R_{670} shows minimum sensitivity to Chl concentration. For a Chl > 20 mg/m^3, R_{670} primarily depends on concentration of non-organic suspended matter (Gitelson *et al.* 1993a; 1994b; Dekker, 1993; Yacobi *et al.* 1995). Reflectance beyond 750 nm depends on both organic and non-organic suspended matter concentrations and is insensitive to algal pigments (Han *et al.* 1994); the variation of R_{750} is comparatively small because of strong water absorption in the NIR range. Thus, the slope of the baseline between 670 and 750 nm depends primarily on scattering by water constituents, but phytoplankton: with variation of non-organic and non-pigmented organic suspended matter concentration, the slope of the baseline changes but it has minimal influence on the height and area of the 700 nm peak above the base line. Therefore, the height of the peak and the area above the baseline between 670 and 750 nm depends mainly on phytoplankton density and was used as its quantitative measure.

The regression of reflectance height at 700 nm above the baseline from 670 to 750 nm (Fig. 4b), as well as area above this baseline (Fig. 4c), and the position of the NIR peak (Gitelson 1992; 1994), against Chl *a* concentrations yielded high correlation coefficients, always $r^2 > 0.90$ (Gitelson *et al.* 1994a; Yacobi *et al.* 1995). The developed algorithms were validated by recurrent experiments in Lake Kinneret, as well as in other environments, including Iowa lakes (Fig. 7a) dominated by diatom algae and Haifa Bay with dinoflagellates and diatoms (Fig. 7b), both with small to

moderate Chl concentrations (Table 1). The algorithms were also used to estimate Chl concentrations in wastewater ponds, where chlorophytes algae dominated with extremely high (70-520 mg/m^3) Chl concentration (Figs. 7c). In all aquatic systems studied, the algorithms proved expedient as tool for Chl concentration estimation.
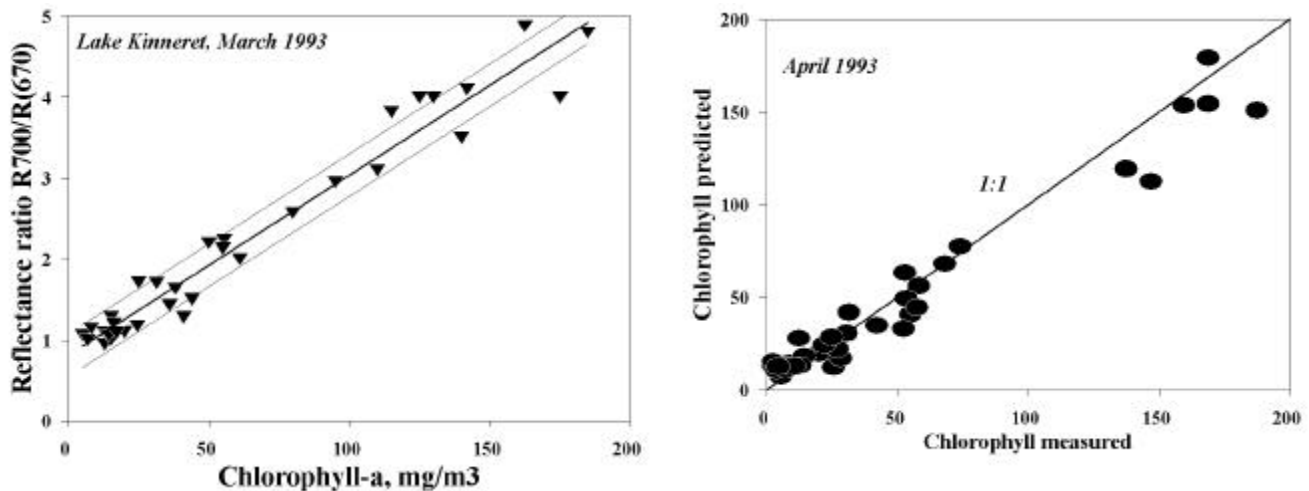

Fig. 6: Validation of the reflectance ratio algorithm, R_{700}/R_{670}, for estimation of Chl concentration in lake Kinneret. Chl concentrations were predicted by ratio R_{700}/R_{670}, measured in April 1993. Relationship R_{700}/R_{670} vs. Chl (solid line), obtained in March 1993, was used to calculate Chl predicted. Then, Chl predicted was compared with actually measured Chl concentrations. Error of Chl prediction, determined as root-mean square deviation of predicted Chl values from actually measured, did not exceed 18 mg/m^3. The slope of the relationship R_{700}/R_{670} vs. Chl changed in various experiments (see Figs 5 and 6). In the cases presented herein, slope of the relationship for Lake Kinneret was at least 50% higher than that of the fishponds.

Basically, in all instances the same algorithms were applied, however coefficients of the relationships between Chl concentration and remotely measured variables should be adjusted for each case separately (Table 2). The suitability of those algorithms for completely different water bodies studied, from oligotrophic and mesotrophic Iowa lakes to hypereutrophic wastewater ponds, underlines the physical rationale behind the choice of the spectral reflectance features used.

For all inland waters studied, excluding wastewater ponds, the coefficients b in the relationships Chl vs. reflectance line height were in agreement (they ranged from 31.8 to 47.2 mg/m^3/% - Table 2). Minimal b value (31.8 mg/m^3/%) was found for Carter Lake, Nebraska in a full annual cycle. Taking into account extremely diverse trophic status of water bodies, the existence of robust relationship between Chl concentration and suggested variables of reflectance must to be taken as proved. Worth to note, that the suitability of the algorithms to estimate the density of phytoplankton in water bodies dominated by blue-greens is of great importance, considering the significance of that algal group as potential environmental hazard.
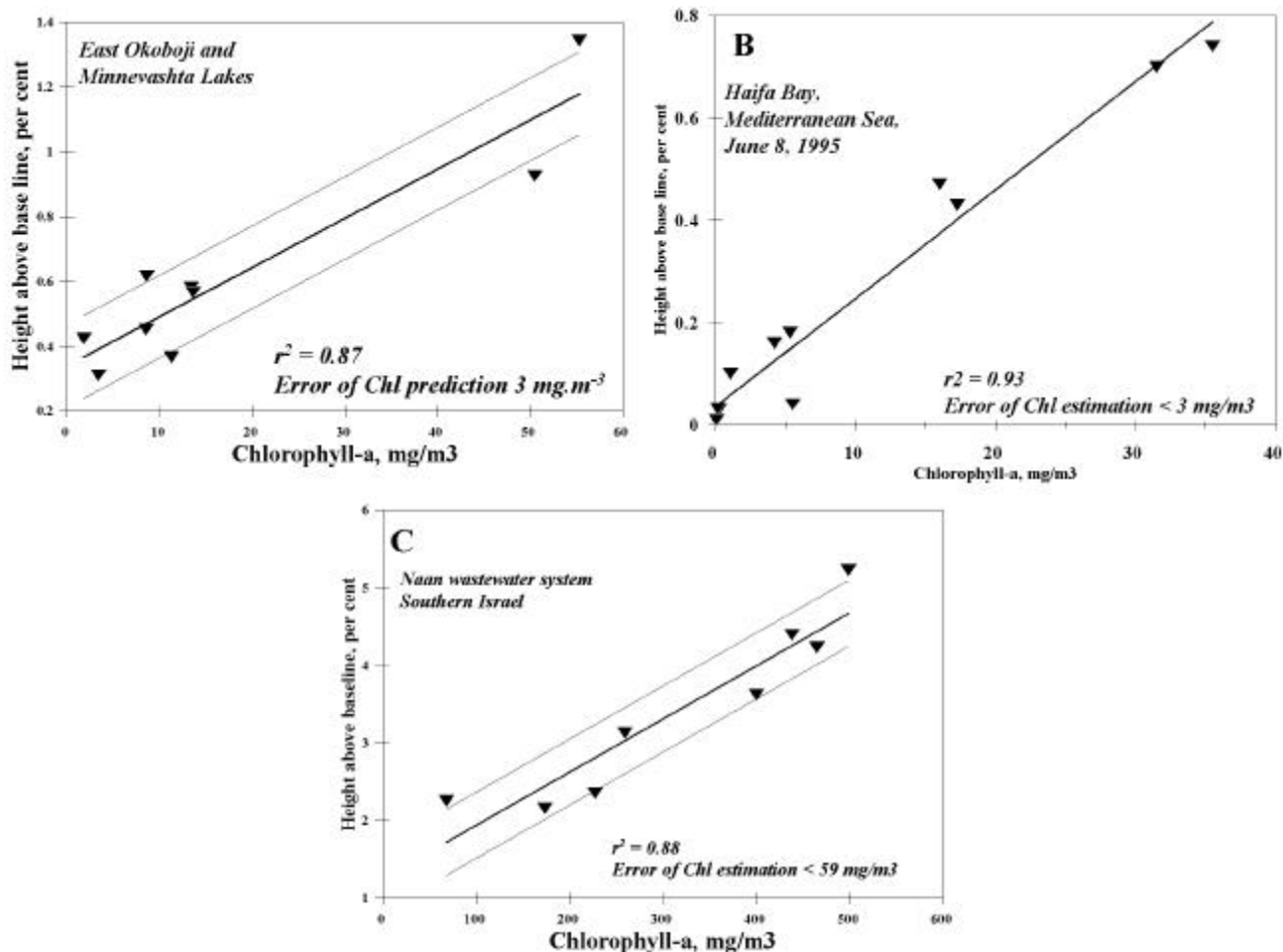
Fig. 7: Validation of the algorithm, height of the peak near 700 nm above a baseline drawn from 670 nm to 750 nm, for estimation of Chl concentration. (a) Lakes in northwestern Iowa, USA, September 1996; (b) Haifa Bay, Southeastern Mediterranean Sea, June 1995; (c) Waste water ponds, Israel, May 1998. The difference in Chl concentrations between the extremes (Fig 7a. and 7c) was at least ten-fold. Nevertheless, in all the systems examined in our studies, we found a linear relationship between the height above the base line and Chl concentration. Note, however, that the coefficients of the relationships changed between experiments (Table 2).

Table 2: Comparison of regression statistics for several studies in which total chlorophyll was regressed against the predictor - reference peak height near 700 nm above baseline from 670 nm to 750 nm ($RLH_{670-750}$):
$Chl = a + b*RLH_{670-750}$; r^2 is determination coefficient.

Site	Period	a	b	r^2
Lake Kinneret	March and April 1993	1.77	40.8	0.96
Lake Kinneret	February 1994	2.27	43.4	0.94
Haifa Bay, Israel	May 1994 and June 1995	4.90	47.2	0.93
Carter Lake, USA	April 1995 to April 1996	6.20	31.8	0.83
Waste water ponds, Israel	May 1996	1.20	18.0	0.88
Iowa lakes, USA	September 1996	2.30	36.0	0.86

Satellite carried sensor future options
A major and unresolved issue is determining whether our findings from high spectral resolution radiometer measurements, obtained at close range, can be applied to satellite sensors with limited spectral resolution. Global maps of algal density (i.e., Chl *a*) in the oceans were achieved using wide band sensors and/or a small number of narrower

channels appropriate for phytoplankton sensing (i.e. the CZCS and SeaWiFS). We infer from our work that the spectral requirements for Chl estimation are quite restricted, and use of an instrument with several narrow (10-20 nm) spectral channels in the red and near infrared ranges should be sufficient. We suggest that an optimum configuration would include channels centered at 600, 625, 650 nm (accessory pigments), 670 nm (Chl absorption and reference for baseline), 685 nm (Chl fluorescence), 700 nm (NIR peak position), and 750 nm (reference for base line). Near future narrow band satellite sensors offer better capability to detect phytoplankton pigments: MERIS (ESA) and MODIS (NASA) aimed to monitor photosynthetic pigments in vegetation and aquatic environments, and its spectral channels (especially of MERIS) coincide in certain degree with the significant spectral features of water constituents in inland waters (Fig. 8). These sensors include spectral channels for atmospheric corrections that is mandatory for monitoring of inland water quality from space.
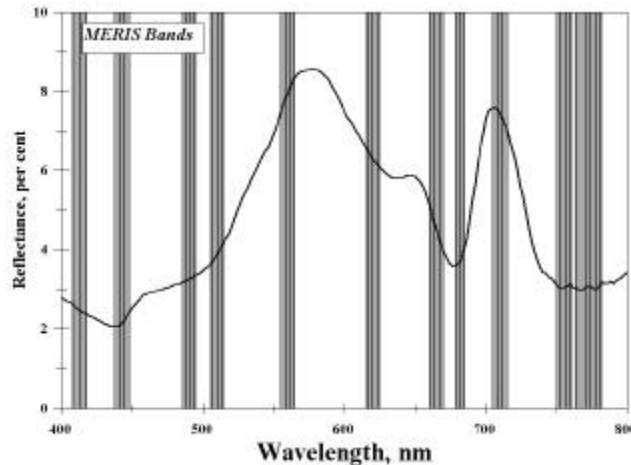

Fig. 8: Typical reflectance spectrum of productive inland waters and the location of the bands of MERIS system.

In order to harness the satellite acquired data for water quality monitoring several steps of operation are mandatory:

- adjustment of algorithms for Chl estimation, developed by the use of high-resolution spectroradiometers at ground level, to the capabilities offered by satellite-carried sensors;
- establishment of a routine for satellite image acquisition, processing and analysis, including geometrical and atmospheric corrections of the images, and selection of the relevant optical information;
- validation of the satellite data by ground observations in diverse aquatic productive ecosystems.

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