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Yosef Z. Yacobi

Yigal Allon Kinneret Limnological Laboratory

Anatoly Giltelson

Ben-Gurion University of the Negev

Meir Mayo

Tel Aviv University

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Remote sensing of chlorophyll in Lake Kinneret using high-spectral-resolution radiometer and Landsat TM: spectral features of reflectance and algorithm development

Yosef Z. Yacobi, Anatoly Gitelson^{1,3} and Meir Mayo²

Israel Oceanographic & Limnological Research, Yigal Allon Kinneret Limnological Laboratory, PO Box 345, Tiberias 14102, ¹J. Blaustein Institute for Desert Research, Ben-Gurion University of the Negev, Sede Boker 84990 and ²Department of Geophysics and Planetary Science, Tel-Aviv University, Israel

³To whom correspondence should be sent

Abstract. High-resolution reflectance spectra in the range of 400–850 nm were obtained from Lake Kinneret during a period when dense populations of the dinoflagellate *Peridinium gatunense* dominated the phytoplankton. Chlorophyll (Chl) concentrations ranged from 5.1 to 185 mg m⁻³ and from 2.4 to 187.5 mg m⁻³ in the samples of two independent experiments. The most prominent features of the reflectance spectra were: (i) a wide minimum from 400 to 500 nm; (ii) a maximum at 550–570 nm, which did not surpass 3% in samples with high Chl concentration (>20 mg m⁻³), indicating a strong absorption by pigments in the green range of the spectrum; (iii) a minimum at 676 nm; this was ~1% and was almost insensitive to variation in Chl concentration >10 mg m⁻³; (iv) a maximum reflectance showed near 700 nm; its magnitude and position were highly dependent on chlorophyll concentration. High-spectral-resolution data were used as a guideline for selection of the most suitable spectral bands for chlorophyll remote sensing. Models were devised, based on the calculation of the integrated area above the baseline from 670 to 850 nm and the reflectance maximal height within this range. Some algorithms already used in previous studies were tested and showed a plausible degree of accuracy when applied to the current data base. However, novel models devised in this study improved substantially the accuracy of Chl estimation by remotely sensed data, by reducing the estimation error from >11 to 6.5 mg m⁻³. Those models were validated by an independent data set where Chl concentration ranged over two orders of magnitude. The use of three relatively narrow spectral bands was sufficient for Chl mapping in Lake Kinneret. Therefore, a relatively simple sensor, measuring only a few bands will be employed in future applications for Chl monitoring in inland waters. Radiometric data were also used to simulate radiances in the channels of TM Landsat and to find the algorithm for Chl assessment. The ratio of channel 4 to channel 3 was used and enabled Chl estimation with an error of <15 mg m⁻³. This algorithm was employed to map Chl in the entire area of Lake Kinneret with 10 gradations.

Introduction

The most conspicuous biological feature of Lake Kinneret is the periodic bloom of the dinoflagellate *Peridinium gatunense* Nygaard (Serruya, 1978; Pollinger, 1986), which displays a visual spatial discontinuous dispersion. The population of *Peridinium* increases with the onset of lake water mixing, and from February throughout May forms a dense crop. At the peak of the *Peridinium* bloom, from a practical view point the lake becomes a 'unialgal culture'. Therefore, any general technique applied for the determination of algal density, e.g. chlorophyll (Chl) concentration, actually measures *Peridinium* density. The horizontal distribution of *Peridinium* is highly irregular and patches of *Peridinium* are usually found (Berman and Rodhe, 1971; Pollinger and Berman, 1975). Fluorometric measurement of Chl *in vivo* (Berman and Rodhe, 1971; Berman, 1972) performed during the

Peridinium bloom, as well as determination of extracted chlorophyll (Berman and Ellias, 1973), revealed the patchy spatial distribution of *Peridinium* in Lake Kinneret. Those studies confirmed previous results based on microscopic observations (Pollinger and Kimor, 1970).

The *Peridinium* patches are of an ephemeral nature, as are most other spatial heterogeneities in aquatic environments. However, the differences between the algal concentration within the patch and beyond its limits are higher than in most other systems. Therefore, any attempt at 'representative' sampling of the lake phytoplankton is a frustrating exercise.

Remote sensing could be an effective method for monitoring the distribution of algae in lake Kinneret. This would provide a synoptic view of the investigated area. Often, only a small number of images can highlight the best sampling locations and aid in the design or improvement of point sampling programs.

Remote sensing studies typically involve the mapping of concentrations of a given variable in water bodies using radiance collected by a sensor placed above the water surface. Quantification of concentrations is usually achieved by the development of empirical or semi-empirical models correlating the radiance (or reflectance), as measured by remote sensor, with the 'ground truth' data.

The spectral area used for remote sensing in Case I waters is limited to the blue and green range (Gordon and Morel, 1983). Attempts to apply Case I-derived algorithms for Case II productive waters have demonstrated their limitation when applied to measurements of waters with high concentrations of Chl and/or suspended and dissolved organic matter (GKSS, 1986).

In several cases, the fluorescence line height has been used successfully for the remote detection of Chl in Case II waters (e.g. Neville and Gower, 1977; Gower, 1980; Doerffer, 1981; GKSS, 1986; Fischer and Kronfeld, 1990). Quantitative accuracy is limited by the varying fluorescent efficiency of different phytoplankton populations and by changes in water absorption that reduce the light available for fluorescence. Although this technique seems to be useful for Chl detection, it is difficult to generalize and make comparisons based on previous studies, especially for inland waters with highly variable bio-optical properties.

The spectral features of reflectance of productive waters were studied in ecosystems with Chl concentrations ranging from 5 to 100 mg m⁻³ (e.g. in inland waters: Gitelson *et al.*, 1986, 1993a,b; Dekker *et al.*, 1992; Quibell, 1992; Dekker, 1993; in artificial ponds: Matthews and Boxall, 1994; Rundquist *et al.*, 1995a,b). It was found that the position and the magnitude of the peak of reflectance near 700 nm strongly depended on Chl concentration (Gitelson *et al.*, 1986; Vos *et al.*, 1986; Gitelson, 1992, 1993b; Matthews and Boxall, 1994; Rundquist *et al.*, 1995). This peak represents increased light scattering by algal cells in a region where Chl absorption declines (at wavelengths near 700 nm) and water absorption increases. Different algorithms based on the properties of the peak near 700 nm were developed. They included: (i) its ratio to the reflectance at 670 nm (Gitelson *et al.*, 1986, 1993a,b; Dekker, 1993; Han *et al.*, 1995; Rundquist *et al.*, 1995a); (ii) the position of this peak (Gitelson, 1992, 1993; Rundquist *et al.*, 1995a); (iii) calculation of the first derivative of reflectance (Rundquist *et al.*, 1995b).

The information available so far suggests that the spectral range from green to near IR should be utilized for constructing algorithms for remote Chl assessment.

Although methods for the quantitative estimation of Chl concentration were established and tested in several case studies (e.g. Gitelson *et al.*, 1986, 1993a,b, 1994a,b; Dekker, 1993; Rundquist *et al.*, 1995a), both qualitative and quantitative interpretation of the data are still incomplete. The optical properties of each 'optically active' constituent (phytoplankton, detritus material, non-organic suspended matter as well as dissolved organic matter) are complex and variable, and their influence on reflectance spectra is still not fully understood.

The first objective of our study was to devise optical models of the lake, relating the reflectance obtained just above the water surface to Chl concentration in the surface water. This was done by the selection of spectral bands that displayed maximal and minimal sensitivity to variation in Chl concentration. Several algorithms were developed to assess Chl concentration, utilizing just a few spectral bands as the first step to employ remote sensing technology in the monitoring of phytoplankton distribution in Lake Kinneret.

The second objective was to use the Landsat Thematic Mapper (TM) data for large-scale monitoring of Lake Kinneret water quality. In order to achieve this goal, high-resolution radiometric data were used to simulate the radiances in different channels of the TM. Then algorithms for the retrieval of Chl concentration from TM images were devised. The TM data were processed using the algorithm and the derived Chl concentrations were compared to *in situ* observations.

Method

Two experiments were carried out in 1993 in Lake Kinneret during the *Peridinium* bloom from 23 to 25 March and from 28 to 29 April. Forty and 37 stations were sampled in March and April, respectively. The sampling scheme was devised to cover as high a variation of Chl and suspended matter (SM) concentrations as possible in each experiment.

At every sampling station, the upwelling radiance of water, L_w , and (indirectly) the downwelling radiance, L_0 (with the aid of a standard reference BaSO₄ plate), were measured by a portable LICOR LI-1800 radiometer in the range from 400 to 850 nm with a spectral resolution of 2 nm. In March 1993, during Landsat overpass, the spectral range was expanded to 1100 nm to simulate the corresponding channel of the satellite sensor. The radiometer was attached to a telescope with a field of view of 15°, which was positioned over the water at a height of 2 m. The 15° optic resulted in an instantaneous field of view of ~50 × 50 cm on the water surface. A microcomputer initiated spectroradiometer scanning and stored the data.

The upwelling radiance of the water, L_w , was measured at least three times. The mean value was used in the analysis. One spectrum was measured for ~25 s; therefore, one set of reflectance measurements took <2 min. Each observed upwelling radiance spectrum of the water was divided by the appropriate upwelling radiance spectrum of the reference plate, giving the reflectance as $R = L_w/L_0$.

To minimize the contribution of specular reflected radiance during clear-sky conditions, the telescope was directed towards the water surface at an angle of

~20° off the nadir, and opposite to the direction of the sun's azimuth, where specular reflectance is at a minimum.

Water was sampled with a 5 l Aberg–Rodhe sampler, 0.0–0.5 m below the surface. Two 100 ml subsamples were immediately filtered and stored on ice in 5 ml 90% acetone. Upon return to the laboratory, 5 ml of 90% acetone were added to the filters and each sample was sonicated for 1 min, and left in the dark overnight at 4°C. The extract was subsequently cleared by centrifugation and measured fluorometrically to determine the Chl concentration (Holm-Hansen *et al.*, 1965).

The Landsat TM image was acquired simultaneously with March measurements taken on the lake when the sky was completely clear and cloud free. The Landsat TM image underwent a geometrical correction process so we could locate the sampling stations and extract radiometric data for validation. As the result of this process, every pixel in the image corresponded to a known location in the study area and the radiometric data for each location were examined. A 3 × 3 pixel window (90 × 90 m), centered on the sample point, was used to extract readings for each of the multispectral bands. These data were then averaged for each sample point to reduce sensor noise (Ritchie and Cooper, 1987).

Atmospheric correction was carried out by an algorithm developed by Fraser *et al.* (1992). Input data for the correction consisted of the TM-measured radiances, view and illumination directions, and aerosol optical thickness derived from ground-measured values of solar transmission (Kaufman and Fraser, 1983). The output data produced were the surface reflectances for corresponding points in the image.

The measurements of transmission of the direct sunlight were performed with a sun photometer with eight spectral channels between 400 and 1030 nm (Kaufman, 1993). Measurements were taken when local sources of atmospheric pollution were not evident. Therefore, we can assume that the atmosphere was spatially homogeneous across the lowest 2–4 km of atmosphere where most of the tropospheric aerosol is present. The optical thickness was measured with an error of ±0.01 to ±0.02 (Kaufman, 1993).

The developed algorithm and atmospherically corrected image data were used to produce a Chl concentration map of Lake Kinneret. Several horizontal stripes were present in the image over the total water area. This made interpretation difficult. This noise is produced by non-conformity of the 16 detectors that scan the area across the path of the satellite movement. To eliminate this noise, a two-dimensional Fourier transform filtering method was used. The filter was applied to 'water' pixels only, masked by using radiance data from the IR channel TM4, to distinguish between land and water. An additional averaging (low-pass) filter was applied to remove random high-frequency noise (a despeckling filter). The filtered lake image was converted from gray levels into shades of blue–cyan and planted in the surrounding land image using the land–sea mask.

Results

The phytoplankton assemblage was dominated by *P.gatunense* in both experiments. Chlorophyll concentrations ranged from 5.1 to 185 mg m⁻³ in March and

from 2.4 to 187.5 mg m⁻³ in April. The nanoplanktonic component was >10% only in samples with Chl concentrations >10 mg m⁻³.

Reflectance spectra

Representative reflectance spectra are presented in Figure 1. For Chl concentrations >20 mg m⁻³, a minimum is seen in the blue range of the spectrum. Reflectance increased in this range with the decrease in Chl concentration. This tendency was more obvious in the domain of 480–520 nm than at the shorter wavelengths. For Chl concentrations >20 mg m⁻³, the reflectance was extremely low, only 1% at its highest.

The reflectance peaked between 550 and 580 nm. The peak width and its magnitude decreased with the increase in Chl concentration. In samples with the highest Chl concentration, reflectance did not exceed 3% due to strong absorption by phytoplankton pigments even at these wavelengths. In the range from 590 to 650 nm, the reflectance spectra of all the samples with a Chl concentration of >10 mg m⁻³ were practically uniform.

A reflectance minimum was found at 670 nm. It was ~1% and was virtually non-dependent upon Chl concentration, which covered a wide range from 10 to >180 mg m⁻³. In samples with low Chl concentration, e.g. 5 mg m⁻³, a small peak was found at 683 nm, corresponding to phytoplankton fluorescence. This peak was consistently found in Lake Kinneret during a low Chl period (Gitelson *et al.*, 1994b).

A red maximum appeared near 700 nm (Figure 1). The first derivative of the reflectance demonstrated the shift of null values from 680 (for Chl = 5 mg m⁻³) up to 712 (for Chl = 185 mg m⁻³). This demonstrates a shift in the reflectance maximum toward longer wavelengths with an increase in Chl concentration.

Chlorophyll detection using high-spectral-resolution data

The index for Chl estimation should depend solely on Chl and no other water constituents, and should not be influenced by survey conditions. Therefore, the wavelength at which only one dominant factor will influence spectral feature variation (beside pure water) will be the most useful for the determination of constituent concentration. Reflectance spectra obtained during the *Peridinium* period showed that the red reflectance maximum, near 700 nm, is the only feature meeting the above criteria. The position of the peak, as well as its magnitude, were closely related to Chl concentration (Figure 1). The SD of reflectance values throughout the entire range from 400 to 850 nm, as well as the coefficient of variation, showed that the sensitivity to Chl variation in the range near 700 nm was 2- to 3-fold higher than in the blue region of the spectrum (Figure 2).

One must also include in the Chl determination index the reflectance at the spectral bands with the minimal sensitivity to variation in Chl concentration. The impact of all other water constituents, excluding Chl, should be uniform for both (maximal and minimal sensitivity to Chl concentration) reflectances. This spectral band was found near 670 nm (Figures 1 and 2).

The index R_{\max}/R_{670} was constructed. R_{\max} is the reflectance at a wavelength corresponding to peak height near 700 nm. The index was compared with Chl

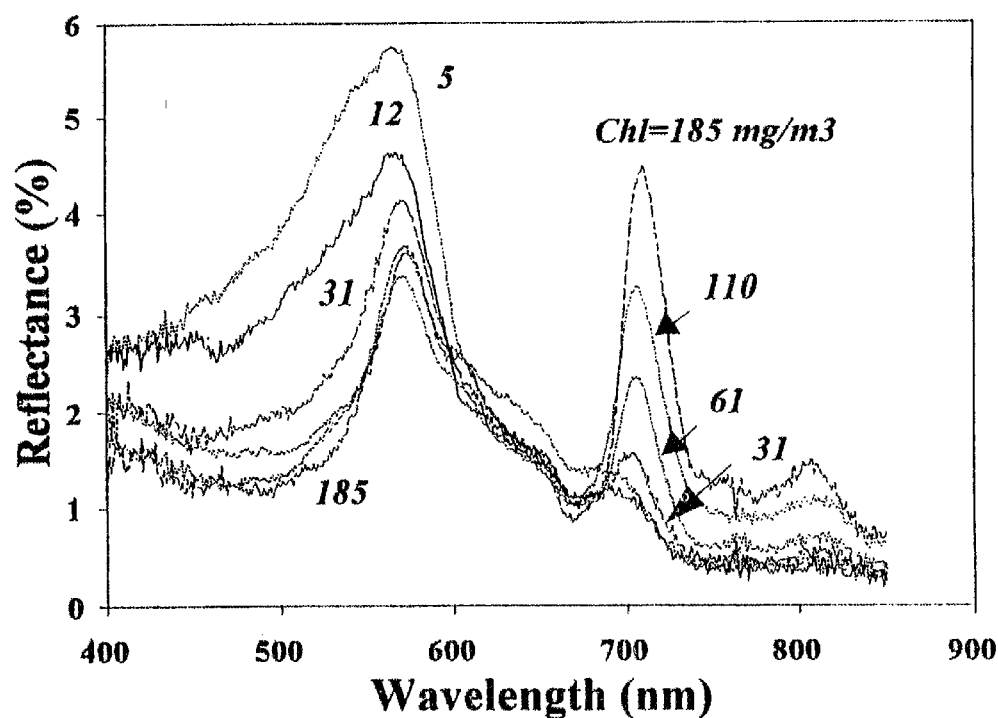


Fig. 1. Reflectance spectra recorded in Lake Kinneret in March 1993. The numbers indicate measured Chl concentrations.

concentration as measured *in situ* (Figure 3a). Linear regressions were computed as follows.

For the March set:

$$\text{Chl} = -32.35 + (43.08 \pm 1.60) \times R_{\text{max}}/R_{670} \quad (1)$$

$r^2 = 0.95$, $n = 41$, with an estimation error of Chl of 11.53 mg m^{-3} .

For the April set:

$$\text{Chl} = -40.04 + (48.00 \pm 1.62) \times R_{\text{max}}/R_{670} \quad (2)$$

$r^2 = 0.96$, $n = 37$, with an estimation error of Chl of 10.9 mg m^{-3} .

The model was validated by an independent data set. We carried out this validation by applying equation (1) (derived from the March set) to calculate Chl concentration by using reflectance measurements that were obtained in April. The resulting predicted values were compared to the *in situ* Chl values measured in April (Figure 4a). The correlation between predicted and measured sets was $r^2 = 0.96$, and the linear regression was

$$\text{Chl}_{\text{pred}} = 5.14 + 0.86 \text{ Chl}_{\text{meas}} \quad (3)$$

with an estimation error for Chl concentration of $<9.55 \text{ mg m}^{-3}$.

The underestimation of the predicted values in comparison with measured quantities derives from our experimental inability to sample both the water parcel and the spectra simultaneously. This point is very important for waters with high

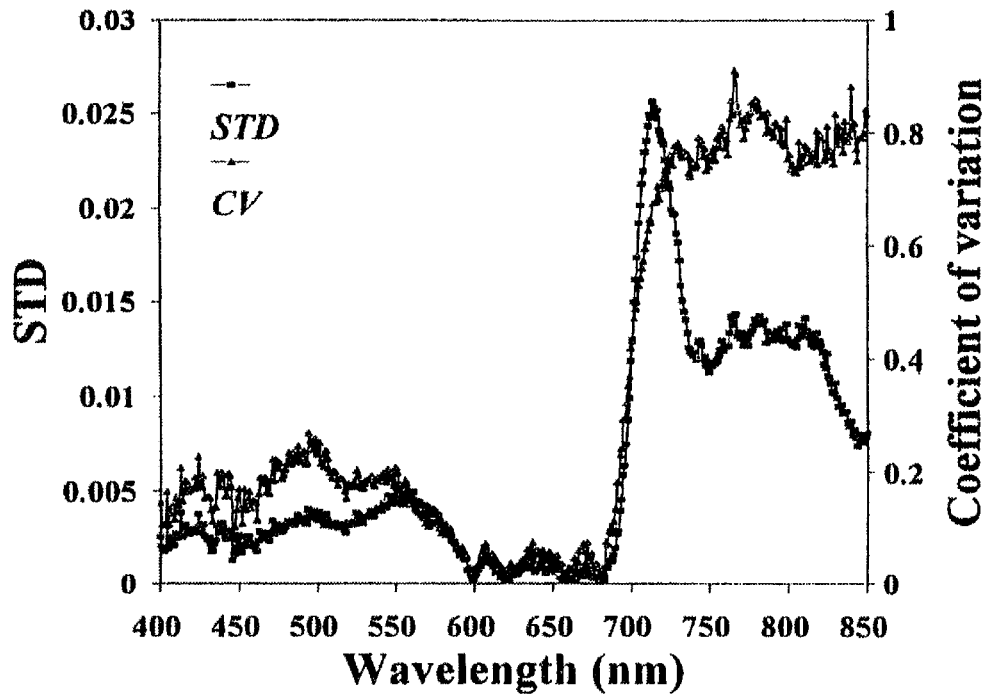


Fig. 2. Spectra of standard deviation (SD) of reflectance and coefficient of variation (ratio of SD to mean reflectance) for the March 1993 data set (40 sampling stations).

spatial and temporal variability of the distribution of suspended solids (see Discussion).

Two new methods of Chl estimation were developed in this study. One of them used the reflectance height at the wavelength corresponding to peak maximum above the baseline, spanned between 670 and 850 nm. The reflectance in this range of the spectrum depends almost entirely on Chl absorption and scattering by phytoplankton (Dekker, 1993; Gitelson, 1992, 1993; Quibell, 1992). The 850 nm point was selected because it is a wavelength at which the variation of reflectance was minimal.

By using the 670–850 nm baseline, we could calculate the reflectance line height (RLH) and compare it to Chl concentration for the two data sets (Figure 3b). The relationship for the March set was:

$$\text{Chl} = 1.77 + (40.77 \pm 1.76) \times \text{RLH}_{660-850} \quad (4)$$

$r^2 = 0.96$, $n = 41$, with an error of 10.5 mg m^{-3} ; and for the April data set:

$$\text{Chl} = 2.27 + (43.42 \pm 0.95) \times \text{RLH}_{670-850} \quad (5)$$

$r^2 = 0.98$, $n = 37$, with an estimation error of Chl of $<6.71 \text{ mg m}^{-3}$.

Equation (4) was validated, by using the April data set (Figure 4b), with the following result:

$$\text{Chl}_{\text{pred}} = 1.07 + 0.91 \text{ Chl}_{\text{meas}} \quad (6)$$

with $r^2 = 0.98$ and an estimation error of chlorophyll of $<6.18 \text{ mg m}^{-3}$.

The second method for Chl estimation used the sum of reflectance above the baseline from 670 through 850 nm as a Chl indicator. The estimation errors of those

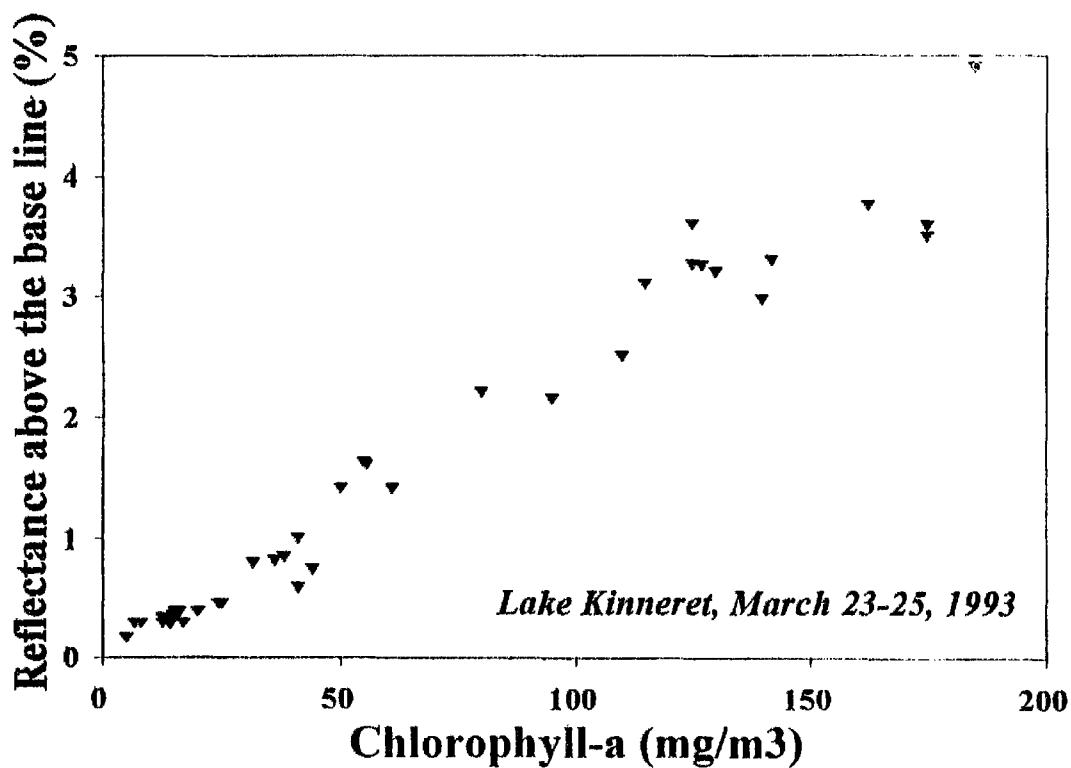
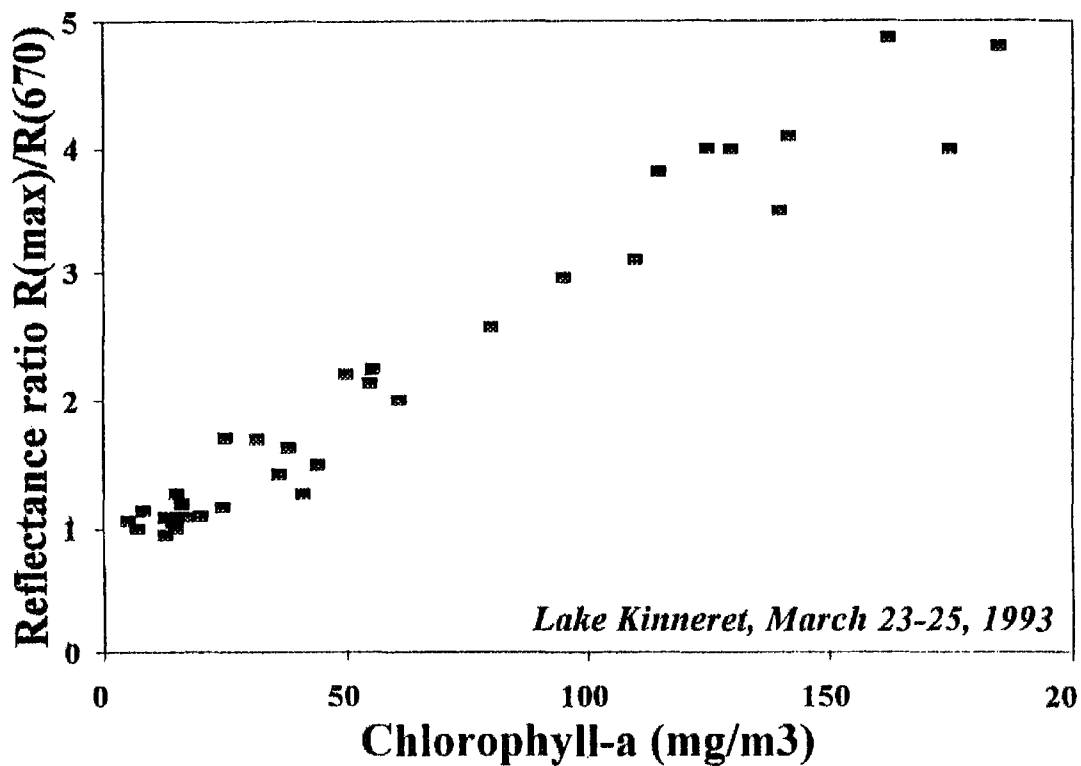


Fig. 3. Pairwise comparison of optical variables plotted against Chl concentration. (a) The ratio of maximal reflectance in the red range (R_{\max}) to the reflectance at 670 nm (R_{670}). (b) The reflectance line height ($RLH_{670-850}$) above the baseline from 670 to 850 nm.

algorithms were found to be of the same order of magnitude as those found from equation (4).

The developed algorithms avoided, to a certain degree, the problems of variation in peak position and its shape. Both accounted not only for height of the peak near 700 nm, but also for the Chl absorption at 670 nm, and enhanced the accuracy of estimations. Variability in the amount of suspended matter caused changes in the slope of reflectance spectra from 600 to 850 nm. This tilted the baseline, but did not prevent accurate determination of the line height and sum of reflectance above the baseline (Gitelson *et al.*, 1994b).

Chlorophyll detection using Landsat Thematic Mapper

The option of using Landsat TM images for the estimation of Chl distribution in Lake Kinneret was investigated by simulation of radiance in the channels of TM by the measured reflectance spectra. The variation of simulated radiance in the third channel TM3 (600–690 nm) was minimal. This indicated that scattering by particles and absorbance by pigments were almost in equilibrium in this range of the spectrum. Maximal variation of simulated reflectances was found in channel TM4 (800–1100 nm). These findings suggest that Chl assessment may be feasible using an index constructed as a ratio of TM4/TM3. This ratio should be maximally sensitive to Chl concentration and, to a certain degree, invariant with respect to survey conditions.

Figure 5 demonstrates the comparison of the developed index (as a ratio of simulated radiances TM4/TM3) with the actual measured Chl concentration. The correlation coefficient (r^2) for a linear relationship was found to be 0.92.

The findings were examined using reflectances extracted from atmospherically corrected TM data. The correlation between TM-derived Chl and measured Chl concentration was $r^2 = 0.79$. The estimation error for Chl was $<15.8 \text{ mg m}^{-3}$. This allowed mapping of Chl ranging from 5 to 185 mg m^{-3} , with 10 gradations (Figure 6). In this false color map, the patchy nature of the phytoplankton spatial distribution is well displayed. The decrease in the accuracy of Chl estimation using TM data was probably caused by very high temporal variation in Chl distribution during our measurements. As a consequence, this hampered our ability to compare accurately remotely sensed data and ground data.

Discussion

Optical properties

The reflectance near 550 nm did not follow the conceptual model of algal reflectance (Gordon and Morel, 1983). In our experiments, we found a negative correlation between algal concentration and the reflectance in the green range of the spectrum (as well as between the simulated radiance in TM2 and algal concentration). Absorption by carotenoids is apparently the reason for this spectral feature. During the *Peridinium* bloom period, peridinin and diadinoxanthin are the most abundant carotenoids (Dubinsky and Polna, 1976). Peridinin absorbs *in vivo* up to 570 nm (Bidigare *et al.*, 1990) and therefore it reduces reflectance in the green range. Scattering by phytoplankton cells (as well as other organic and non-organic

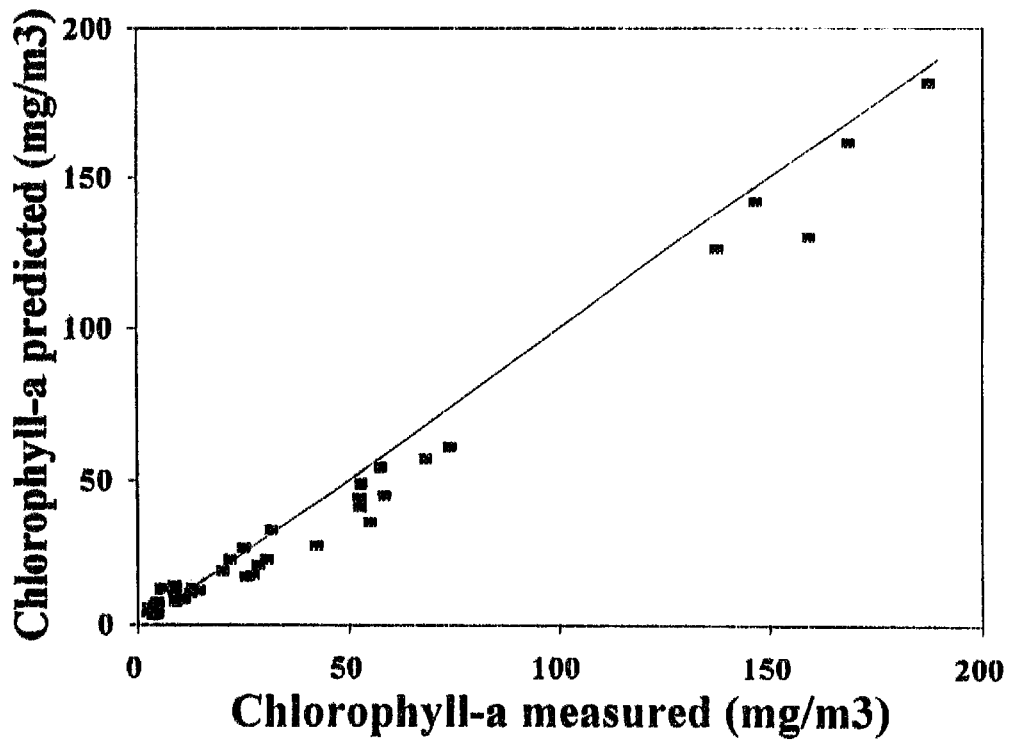
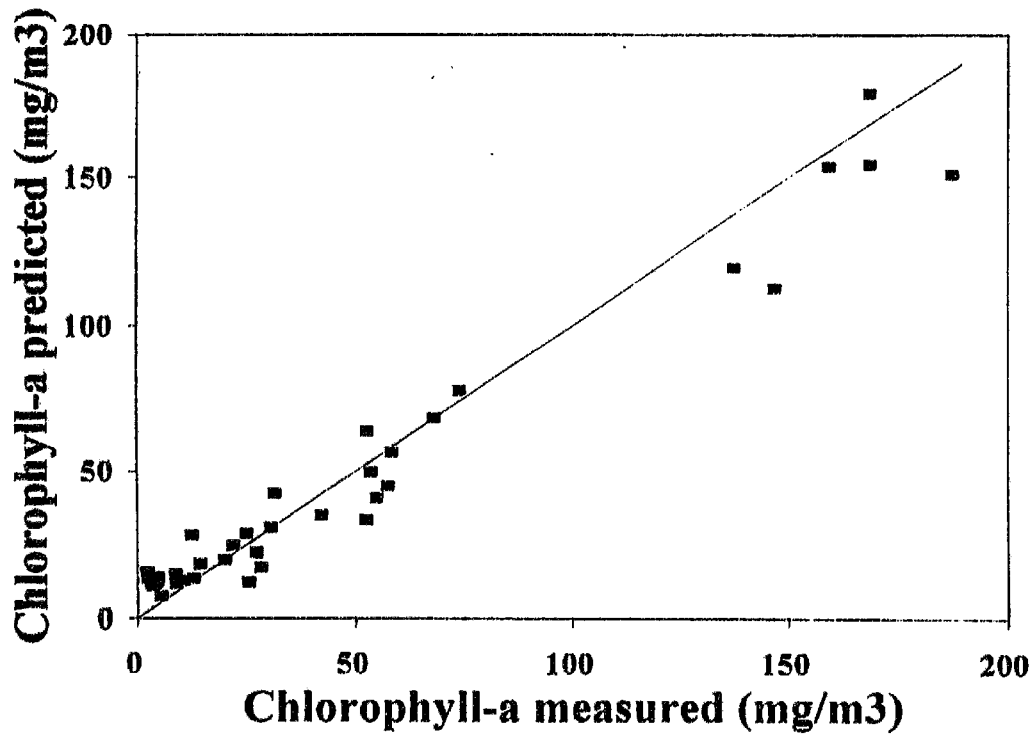


Fig. 4. Validation of the models presented in Figure 3 by data sets acquired in April. (a) Equation (3)— R_{max}/R_{670} , (b) equation (6)— $RLH_{670-850}$.

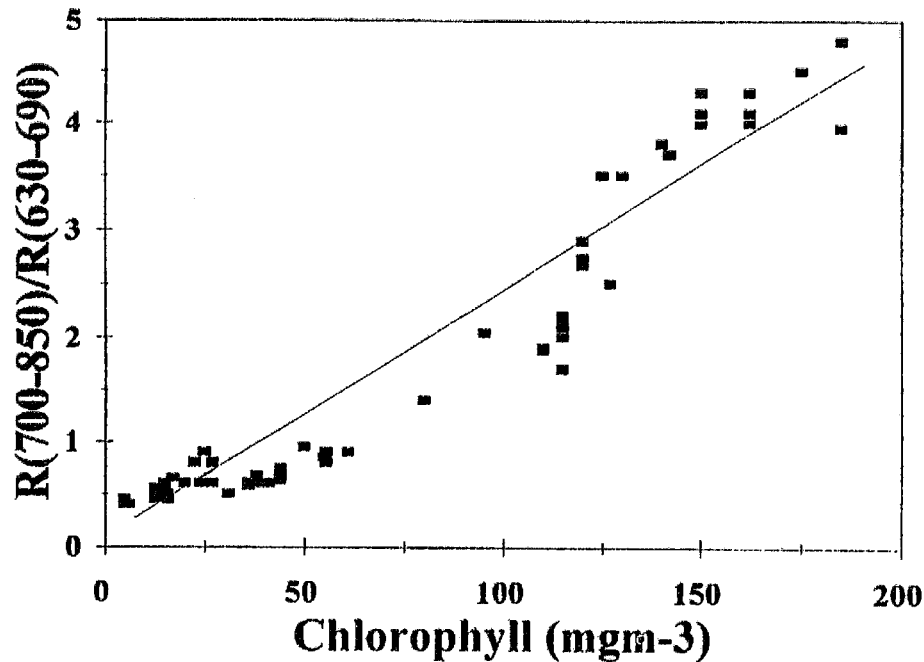


Fig. 5. Ratio of simulated radiances in the channels of Landsat TM versus measured chlorophyll concentrations.

particles) also affects the spectral behavior of reflectance. A decrease in reflectance when Chl increases confirms the finding that absorption is dominant over scattering in this spectral range. This is, apparently, a feature of *Peridinium* (and other chromatophytes) that distinguishes them from green and blue-green algae (e.g. Quibell, 1992; Dekker, 1993; Rundquist *et al.*, 1995a). Absorption by peridinin, which *in vivo* peaks in the range from 490 to 510, is the governing factor of reflectance in the green region. This can be explained by the enormous concentrations of *Peridinium* during the bloom period.

It was discovered recently that the reflectance at 670 nm remains almost constant over a wide range of Chl *a* concentrations (Gitelson *et al.*, 1986, 1993a,b; Dekker, 1993; Rundquist *et al.*, 1995a). When phytoplankton density increases, the reflectance near 670 nm should also increase, due to elevated scattering by phytoplankton cells. Concurrently, the increase in Chl *a* absorption should lead to a decrease in reflectance. When the Chl concentration is $>10 \text{ mg m}^{-3}$, the processes of absorption and scattering are almost in equilibrium, and phytoplankton density hardly affects the reflectance at 670 nm at all. Therefore, reflectance at 670 nm primarily depends on the concentrations of non-pigmented organic and non-organic suspended matter.

A decrease in Chl absorption and an increase in pure water absorption result in a minimum of the combined absorption curve of algae and water near 700 nm (Vasilkov and Kopilevich, 1982; Gitelson *et al.*, 1986; Vos *et al.*, 1986; Gitelson, 1992, 1993). An increase in algal density leads to enhancement of scattering and, as a consequence, to increased reflectance, which shifts the peak position towards longer wavelengths.

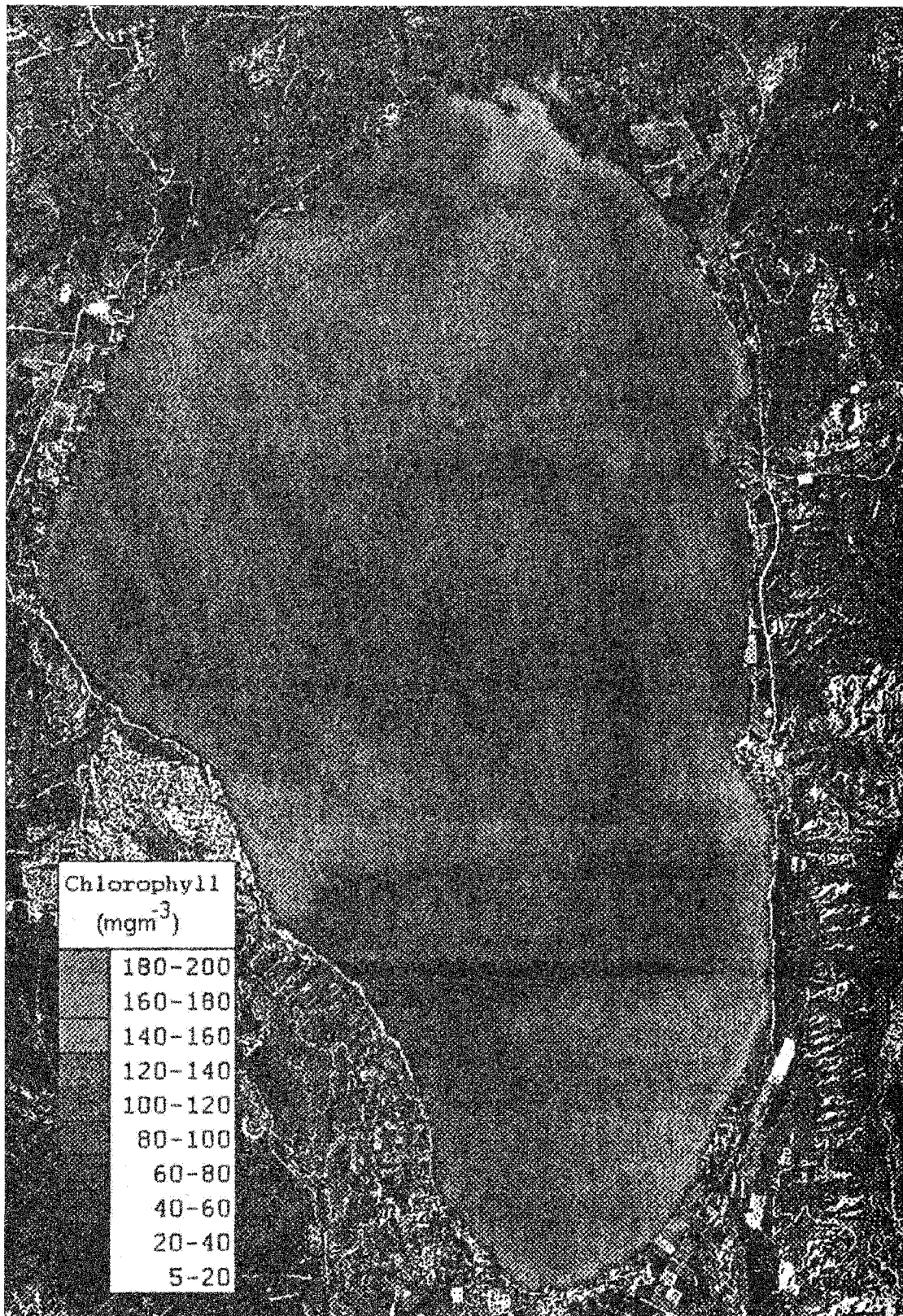


Fig. 6. False color map of phytoplankton distribution in Lake Kinneret, produced from the radiance ratio TM4/TM3. The Landsat TM image was acquired on 23 March, 1993.

For Chl concentrations of $>20\text{--}30\text{ mg m}^{-3}$, scattering by phytoplankton cells is the dominant factor in the near-IR region of the spectrum, and governs the spectral behavior of reflectance. The same effects were found to be dominant for green and blue-green algae (Quibell, 1992; Rundquist *et al.*, 1995a,b). On the other hand, these observations are significantly different from observations in productive coastal waters, where the region near 680 nm (natural fluorescence signal) was considered the most appropriate for gathering information on Chl concentration (GKSS, 1986; Fischer and Kronfeld, 1990).

Spatial and temporal variation

The stability of the proposed models depends on several factors. The main group of factors relates to the inherent optical properties of algal cells, non-organic and detrital particles. Therefore, the parameters to be used in the models pertain to the nature of suspended and dissolved water constituents. Change in taxonomic composition of the phytoplankton, the intrinsic organization of pigments within cells ('package effect'), the particle size distribution of non-living materials and the nature of dissolved matter will affect the reflected signal. From studies of the vertical attenuation coefficient of Lake Kinneret, we know that the underwater light field undergoes dramatic changes throughout the year (Dubinsky and Berman, 1979). It can be seen that the 'background' of the attenuation coefficient increases significantly with the increase in phytoplankton biomass density. We have also noted in our preliminary studies that the nature of the reflectance is variable throughout the year (Gitelson *et al.*, 1994a). Some of the changes may be partly attributed to variations in the inherent optical properties of the water constituents, and partly to differential proportions between different components of the suspended matter. Thus, for example, the linear correlations between Chl and SM concentrations were $r^2 = 0.71$ and 0.68 , in March and April, respectively. These values are considerably higher than the $r^2 = 0.31$, which was found in Lake Kinneret during a low Chl period (Gitelson *et al.*, 1994b).

Reflectance spectra acquired in a very limited area of Lake Kinneret during *Peridinium* bloom may be highly variable. The reflectance spectra presented in Figure 7 were collected at three sampling stations, spaced ~ 10 m apart in a tiny sheltered bay. Yet, the measured chlorophyll concentrations were 46, 112 and 170 mg m^{-3} . This phenomenon is even more pronounced in the pelagic waters of the lake, and algal concentration variation can often be detected visually.

Another group of factors which influence the stability of the parameters used in the proposed algorithms relate to some technical limitations in our measurement method and equipment. During field data acquisition, we often found a 2-fold difference in Secchi depth measured on two sides of the boat spaced 2.5 m apart. Water motion induces further temporal variation of algal distribution, therefore several spectra collected at a given point within 2–3 min may be highly variable. In Figure 8, four spectra are presented and the difference between the extremes is $\sim 300\%$. This finding is an indication that firm 'ground truth' can hardly be achieved from so temporally variable a source as *Peridinium* populations during the bloom of this alga. Consequently, we have to assume that our 'ground truth' is

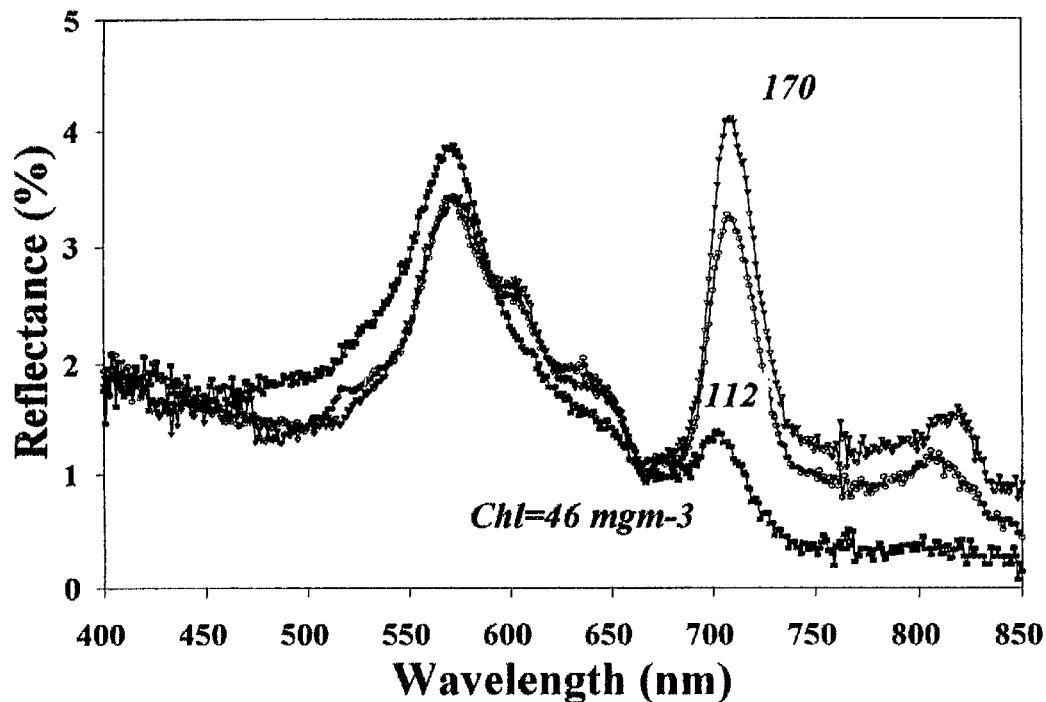


Fig. 7. Reflectance spectra recorded in Lake Kinneret in a sheltered offshore location. The numbers indicate measured Chl concentrations.

just an approximation of the sample which was spectrally measured rather than its concrete representative. The duration of the spectral measurement in our experiment was 25 s. The technical drawback of time mismatch between the water sampling and spectral measurement could be diminished if the latter were collected by a faster instrument.

Limnological considerations

A major issue of remote sensing of algae is the question of the correlation of the radiance emitted from the water surface, i.e. the concentration of algae at the surface, and the vertical distribution of algae throughout the entire water column. The vertical movement of *Peridinium* throughout the diel cycle was studied in Lake Kinneret (Pollinger, 1988). It was found that *Peridinium* migrated upward from the early morning until the afternoon, and then sank downward from late afternoon until midnight. Strong winds suppressed the upward vertical movement and induced aggregation of *Peridinium* cells on top of the thermocline. Dinoflagellates are capable of directional movement, and vertical migration was assumed as an optimization mechanism, that enables the algae to occupy a suitable niche at any given period of time (George and Heaney, 1978; Heaney and Talling, 1980). Light requirements, nutrient availability and the cellular concentration of heavy photosynthesates are presumably the factors driving dinoflagellate vertical movements (Talling, 1971; Heaney and Epply, 1981).

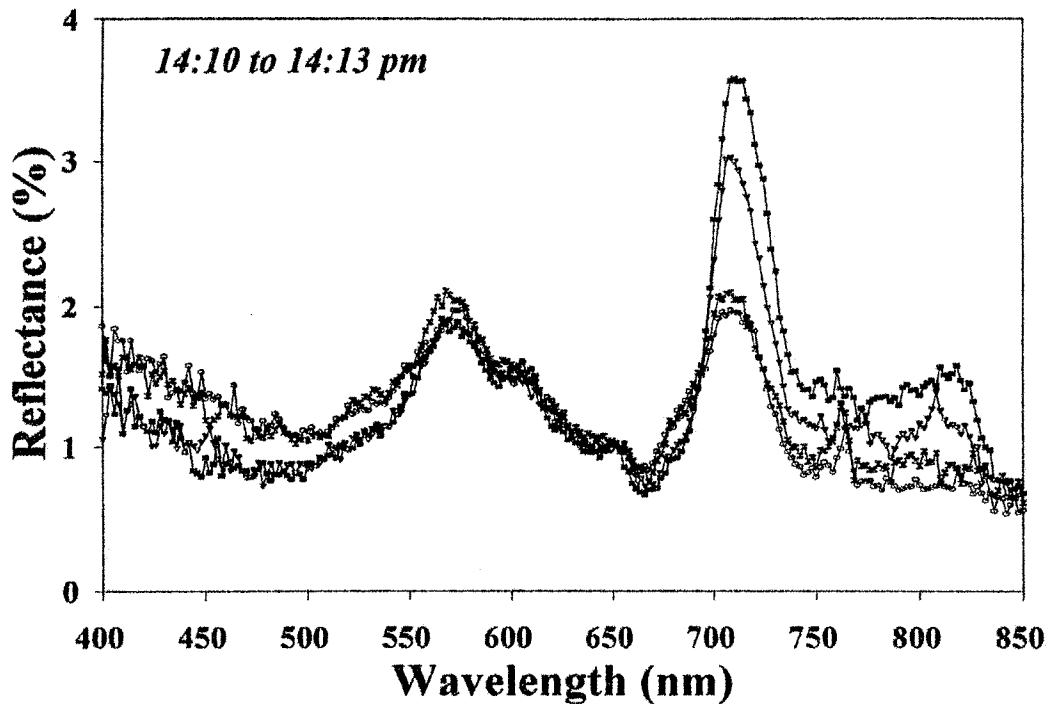


Fig. 8. Reflectance spectra recorded in Lake Kinneret within 3 min in a pelagic station.

It is obvious that the relationship between cell concentration at the surface and cell concentration in the entire water column is subject to wide seasonal and diurnal variation (Berman and Rodhe, 1971; Pollinger and Berman, 1975; Pollinger, 1988). Remote sensing of Lake Kinneret during *Peridinium* bloom is, therefore, limited as a tool for phytoplankton biomass estimation. However, if the relationship between the surface cell concentration and the total concentration of the algae varies within a relatively narrow range, remote sensing may be used for monitoring the spatial distribution of *Peridinium*. A series of measurements showed that the mode of vertical alignment was quite consistent when several stations were sampled within a short time span (Berman and Rodhe, 1971). We found that the concentration of *Peridinium* observed at the surface correlated plausibly with the integrated concentration of this alga in the upper 10 m water column when checked at 26 stations within 5 h (Figure 9). Although much effort is still required to evaluate the above-mentioned relationship, we assume that the patchiness of *Peridinium* observed at the surface is due to a three-dimensional structure and is not the result of differential vertical distribution. Therefore, sampling of vertical profiles at several stations should be used as a supplement to remote sensing for the assessment of algal biomass during *Peridinium* bloom in Lake Kinneret.

Satellite-carried sensors

It should be noted that the optical sensors carried by existing spacecraft are not specifically designed to monitor water color. The sensor bands are too wide to be able to detect features as specific as those that were revealed in our study. Yet, the results of the current TM analysis of Lake Kinneret (as well as during a low Chl

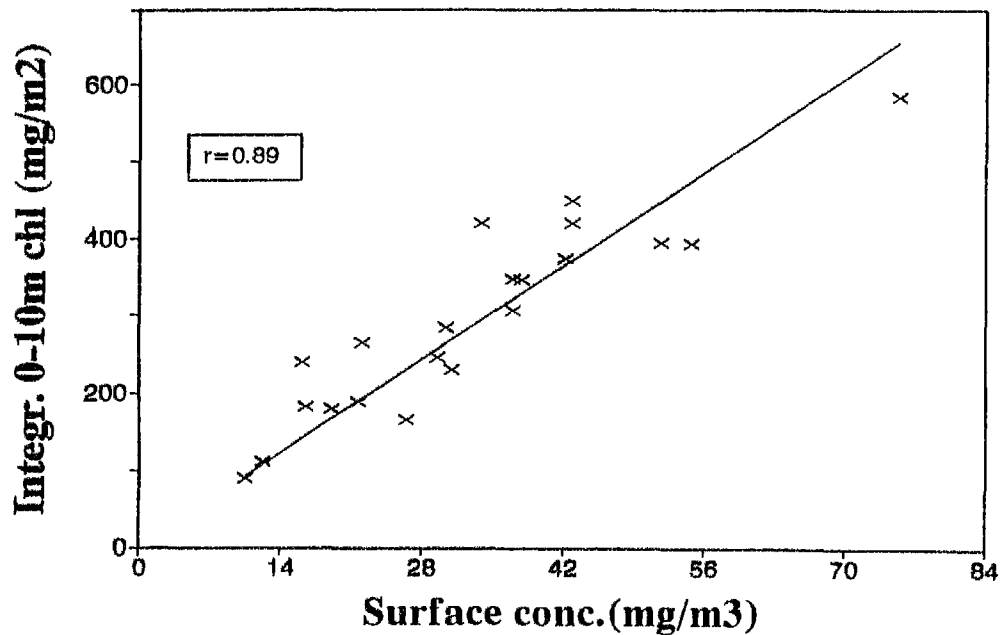


Fig. 9. The correlation between surface Chl concentration and integrated 0–10 m water column chlorophyll concentration, recorded on 9 April, 1991 (Y.Z.Yacobi, unpublished).

concentration period; Mayo *et al.*, 1994), are not completely disappointing—the information derived is unique and could not be gained from any other source.

Our results suggest that for real-time monitoring of phytoplankton bloom development, even images taken from the NOAA satellite AVHRR with spatial resolution of 1×1 km, can be used as an early warning monitoring system.

Conclusions

In the long run, the full potential of remote sensing for investigation of inland waters will be realized through the construction of physically based models. Those models should describe the scattering and absorption of radiation, and the relationships between constituent concentrations and the optical properties of inland waters. However, over short and medium time spans, this approach may be difficult to implement due to lack of information on the essential inherent parameter-specific optical properties of inland waters. We are therefore left with the option of using more empirical approaches, of which spectral indices constitute the major category. For such an approach, the observed spectral features and understanding of their sensitivity to variation in each constituent concentration are extremely important. The findings of this work support earlier results that the spectral range from green to near IR is a suitable source for algorithm construction for Chl assessment in inland and productive coastal waters (Gitelson *et al.*, 1986, 1993a,b, 1994a,b; Fischer and Kronfeld, 1990; Quibell, 1992; Dekker, 1993; Rundquist *et al.*, 1995a,b). The novel algorithms devised in this study enhanced the precision of Chl determination and thus surpassed the existing algorithms for use in Lake Kinneret during *Peridinium* bloom. Using Lake Kinneret as a case study, we assume that the developed models can be applied for remote assessment of Chl in other eutrophic inland waters.

For the remote assessment of Chl in inland productive waters, a sensor for the measurement of radiance with three spectral bands, 670 and 710 nm (with bandwidth 10 nm) and 850 nm (with bandwidth up to 40 nm), should be sufficient.

The stability of the models depends on the temporal and spatial stability of the inherent optical properties of the constituents. Further investigation is required in order to clarify whether the parameters of the models are constant with time in the sampling area.

Remotely operated sensors for real-time monitoring of water quality may not only be carried on satellites and aircraft, but may be installed on ships or in a stationary observatory. These shipboard or stationary platforms should carry imaging sensors with a few specific narrow spectral bands. They are relatively inexpensive and are not limited by uncontrolled restrictions, such as the timing of a satellite overpass, and can be deployed with more flexibility (with respect to both temporal and spatial scales). They seem particularly promising for monitoring relatively small areas of investigation, but can also cover large areas for synoptic mapping.

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