GIS application for mapping of phytoplankton using multi-channel fluorescence probe derived information

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Abstract A submersible multi-channel fluorescence probe was recently introduced in Lake Kinneret, Israel, that enables the determination of phytoplankton density, in terms of chlorophyll $a$ concentration, in real time, and provides information on the contribution of colour-classes to the bulk of algal biomass. Using the GIS Arcinfo software package we could also derive information on the distribution of phytoplankton in different water layers. We found that the vertical distribution of phytoplankton in the epilimnion was mostly fairly uniform, and can be reliably represented by a water layer where the phenomenon of fluorescence quenching is not detectable, i.e. at the depth of 4–6 m. When motile algae dominated the lake phytoplankton the layer of maximum chlorophyll concentration was used. The capability for phytoplankton mapping, almost synoptically, provides an expedient tool for acquisition of ground-truth information for the calibration and/or validation of information derived by remote-operated sensors, carried on-board aircraft or satellite.

Key words chlorophyll $a$; fluorescence quenching; phytoplankton mapping

INTRODUCTION

Phytoplankton is the major vegetative component in most water bodies, both in terms of biomass and the share in the rate of photosynthetic activity. Phytoplanktonic algae are the principle constituent for generation of new particulate organic matter and the production of oxygen, and thus are vital for the fueling of most aquatic environments. Consequently, the density of algae is considered a key parameter for assessment of water quality. Direct determination of algal biomass is a slow, tedious and expertise-requiring procedure, due to the high taxonomic and morphological diversity of all the forms included in the operational term of “algae”. Fortunately there is a shortcut for the estimation of algal biomass, by the measurement of the concentration of chlorophyll $a$ (Chl $a$). That molecule is common to all oxygen-evolving photosynthetic organisms (higher plants and algae), is easily extracted and is characterized by its optical properties. The combination of the ecological significance and feasibility of measurement is apparently the reason Chl $a$ is the most frequently used biological variable in aquatic sciences. The optical activity of Chl $a$ can also be measured in living cells, either in the laboratory or in situ, using fluorescence, absorption or reflectance (Falkowsky & Raven, 1997). In addition to Chl $a$, all algal cells harbour accessory pigments. In contrast to Chl $a$, the distribution of the accessory pigments is not universal, but restricted to one or few algal divisions (Jeffrey et al., 1997). The quantitative determination of the accessory pigments enables the estimation of the share of colour groups in the bulk of phytoplankton.
The unique optical activity of Chl $a$ is the basis for estimation of phytoplankton density by remotely operated sensors. Remote sensing of Chl $a$ is practised on a scale that ranges from small water bodies, like fishponds, up to a global coverage of the oceans. However, the algorithms used for the interpretation of the optical information in terms of Chl $a$ concentration, are either empirical, or semi-analytical, and therefore they should be calibrated by determination of Chl $a$ concentration in discrete samples taken from the water body in question. Another built-in limitation of remote sensing of Chl $a$ is the restriction of the information to the uppermost water layers, which may differ conspicuously from the deeper layers.

In this work the three-dimensional (3-D) distribution of phytoplankton on a whole ecosystem scale (lake) was studied using a submersible probe, which enables rapid acquisition of data. The goals of the work were: (a) to construct a whole lake budget of phytoplankton and its components (in terms of colour groups), and (b) to investigate the feasibility of the acquired data for use as ground-truth for remotely operated sensors. The current report relates to the latter goal.

**METHODS**

The distribution of phytoplankton was measured by a submersible multi-channel probe (FP = Fluoro Probe, bbe Moldaenke, Kiel, Germany), capable of recording fluorescence emitted by vegetative cells, and is designed for the estimation of phytoplankton density and the recognition of several algal groups, based on their content of accessory pigments (Beutler *et al.*, 2002). The discrimination of algal groups is based on accessory pigments activity and is calibrated by the instrument producer to recognize four groups: chlorophytes, chlorophyll $c$-containing algae (e.g. diatoms, dinoflagellates), cryptophytes and cyanophytes. We re-calibrated the instrument with algal strains isolated from Lake Kinneret, as the producer calibration did not yield satisfactory results, and added another colour group of phycoerithrin-containing cyanophytes. It seems that location-suited calibration is mandatory for the generation of reliable data (see Leboulanger *et al.*, 2002).

The work reported here was done in Lake Kinneret, Israel and covers the period from June 2001 to April 2002. Detailed description of the lake was published previously (Berman *et al.*, 1995). The sampling of the medium-size water-body (surface area of about 165 km$^2$) was carried out by deploying the FP at about 30 stations, and was usually accomplished within 4–5 h. Water samples were taken for determination of Chl $a$ extracted from particles collected on GF/C filters in 90% acetone by the routine procedure used in our laboratory (Holm-Hansen, 1965).

The data recorded by the FP were treated by a GIS software package, Arc Info 8.1 for production of maps and calculations of phytoplankton distribution in different water layers.

**RESULTS**

**The timing of measurement/fluorescence quenching**

When data collection occurred during the daytime we could observe the phenomenon of fluorescence quenching, i.e. reduction of the ratio: fluorescence intensity/
concentration of extracted chlorophyll, with increasing light flux (Fig. 1). It is a known phenomenon and is a result of partial damage to the photosynthetic apparatus of algae by excessive light input, such as the light found close to the water surface (Falkowsky & Raven, 1997). The intensity of the damage rises with the increase of impinging light on the water surface, and, consequently as the measurement time gets closer to the solar noon, and the difference between the chlorophyll concentration measured by the FP, and the chlorophyll measured by wet laboratory analysis, increases (Fig. 1). One solution to avoid confusion is to perform the sampling during night-time, when fluorescence quenching is not a problem, but then we are losing the opportunity to match remotely sensed reflectance and Chl $a$ determination done at the water column. We realized that below the depth of 4–6 m fluorescence quenching is no longer detectable; we therefore chose that lake layer to represent the surface water. Fluorescence quenching is probably quite uniform for different algal groups, since it does not deform the distribution of taxons, even if the absolute concentration of chlorophyll declines conspicuously.

Using the wet laboratory data collected in the years 2001–2002 we found that a high correlation exists between Chl $a$ concentration at the surface and deeper layers. Thus, for instance the relationship between Chl $a$ concentration at the surface vs Chl $a$ concentration at 5 m was:

$$\text{Chl } a_{5m} = 0.96 \cdot \text{Chl } a_{\text{surface}} + 0.31, \ (r^2 = 0.91, \ n = 48, \ P < 0.0001)$$

for Chl $a$ concentration ranging between 4 and 38 mg m$^{-3}$, with an estimation error of Chl $a$ of <2.25 mg m$^{-3}$. We therefore felt confident in extrapolating the FP measurements at the depth of 4–6 m to the lake surface for the sake of mapping and establishment of a ground-truth basis for remote sensing.

**The vertical distribution of phytoplankton**

Apart from the impact of fluorescence quenching, in most cases we found a clear correspondence between the thermal structure of the water column and the vertical
distribution of phytoplankton, with relatively high concentrations of Chl $a$ in the epilimnion and prominent decline of densities below the thermocline. The taxonomic composition of the phytoplankton was fairly uniform in the epilimnion, but changed conspicuously in the metalimnion and in the hypolimnion. On a few occasions a thin film of cyanophytes formed at the surface. It could not be detected by the FP deployed normally in the lake, but could be observed in water samples skimmed from the surface and examined in a vessel onboard. When the lake was fully mixed thermally the vertical distribution of the phytoplankton was also fairly uniform down to the bottom of the lake. When the large centric diatom *Aulacoseira granulata* prevailed in the lake at the time of the survey we found an increase of algal concentration towards the bottom, probably as the result of accumulation of sinking cells. The dinoflagellate *Peridinium gatunense* was observed in the period reported herein prior to the thermal stratification of the lake and its vertical distribution noticeably deviated from uniformity. Large alga tends to concentrate in the upper part of the water column, therefore when *Peridinium* dominates the lake the concentration of phytoplankton in the lower parts of the water column is conspicuously lower than that close to the surface.

The spatial distribution of chl $a$ in the “surface” layer

The display of the “surface” Chl $a$ distribution was done by mapping the 4–6 m layer (Fig. 2a) for most surveys. The reason for avoiding the use of the information for the real surface is explained above. We calculated the linear correlation between the average concentration of Chl $a$ at the 4–6 m layer to the average concentration found in the 0–10 m uppermost layer of the lake (Table 1), and found that the coefficient of correlation between the two data sets was mostly high. We therefore we assume that the mapped layer faithfully represents the epilimnetic waters of the lake. The average concentration of Chl $a$ in the 4–6 m layer was fairly similar to the average of the 0–10 m layer, with one exception, when a high concentration of the pigment were found at the lower part of the epilimnion.

If a real vertical gradient of Chl $a$ concentration occurs the decision as to which water layer to consider as representative for surface water is not easy. Such a situation exists when motile or floating algae dominate the lake phytoplankton. Normally in Lake Kinneret the most common species from March to May is the dinoflagellate *Peridinium gatunense*, which tends to concentrate close to the water surface during daytime (Berman *et al.*, 1995). The years 2001 and 2002 were exceptional as the concentration of *P. gatunense* in the lake was small (it re-appeared extensively in 2003). When *P. gatunense* dominates the lake phytoplankton, the surface Chl $a$ concentrations are often genuinely lower than the concentrations found at lower layers. It is well known from the long-time database existing in Lake Kinneret, but we were not able to quantify the deviation induced by the fluorescence quenching. The only survey in which we found relatively high concentrations of dinoflagellate in the time period covered by this report, was in April 2002. The correlation between the extracted Chl $a$ from samples collected at the surface layer and the concentrations recorded by the FP in the surface water was poor. On the other hand it was plausible at the depth
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Fig. 2 The spatial distribution of Chl $a$ concentration in Lake Kinneret, Israel, in: (a) 21 November 2001. The database used for mapping was that of the average measurement taken at 4–6 m depth. The phytoplankton at that survey was dominated by cyanophytes; (b) 22 April 2002. The database used for mapping was that of the average measurement taken at 1–3 m depth, where the maximum Chl $a$ concentration was found in most measuring stations. The phytoplankton at that survey was dominated by dinoflagellates.

Table 1 Chlorophyll $a$ concentration (mg m$^{-3}$) in the layer of 4–6 m, its relationship to the Chl $a$ concentration in the uppermost layer of 0–10 m, and the dominant phytoplankton in Lake Kinneret in 10 surveys. The measurement of chlorophyll concentration and the contribution of different phytoplankton groups was conducted with a multi-channel fluorescence probe (FluoroProbe, bbe Moldaenke, Kiel, Germany) in 31 sampling stations.

<table>
<thead>
<tr>
<th>Date</th>
<th>Chl $a$ conc. average ± std</th>
<th>The relationship between Chl $a$ 4-6 m vs Chl $a$ 0-10 m</th>
<th>Dominant phytoplankton</th>
</tr>
</thead>
<tbody>
<tr>
<td>11 June 2001</td>
<td>5.8 ± 1.00</td>
<td>0.94x + 0.47, $r^2=0.87$</td>
<td>chlorophytes</td>
</tr>
<tr>
<td>19 July 2001</td>
<td>7.2 ± 1.01</td>
<td>0.62x + 2.14, $r^2=0.64$</td>
<td>cyanophytes</td>
</tr>
<tr>
<td>15 Aug 2001</td>
<td>6.8 ± 1.41</td>
<td>0.45x + 2.95, $r^2=0.48$</td>
<td>cyanophytes</td>
</tr>
<tr>
<td>4 Sept 2001</td>
<td>11.3 ± 1.35</td>
<td>1.21x - 3.11, $r^2=0.90$</td>
<td>diatoms</td>
</tr>
<tr>
<td>15 Sept 2001</td>
<td>5.7 ± 0.71</td>
<td>0.82x + 0.65, $r^2=0.64$</td>
<td>cyanophytes</td>
</tr>
<tr>
<td>21 Nov 2001</td>
<td>9.0 ± 1.14</td>
<td>0.90x + 0.91, $r^2=0.92$</td>
<td>cyanophytes</td>
</tr>
<tr>
<td>30 Jan 2002</td>
<td>21.9 ± 2.97</td>
<td>1.14x - 5.71, $r^2=0.72$</td>
<td>diatoms</td>
</tr>
<tr>
<td>14 Feb 2002</td>
<td>21.6 ± 5.83</td>
<td>1.13x - 3.70, $r^2=0.84$</td>
<td>diatoms</td>
</tr>
<tr>
<td>12 Mar 2002</td>
<td>16.2 ± 4.74</td>
<td>0.68x + 7.32, $r^2=0.62$</td>
<td>chlorophytes</td>
</tr>
<tr>
<td>22 Apr 2002</td>
<td>20.3 ± 7.62</td>
<td>0.82x + 3.15, $r^2=0.79$</td>
<td>dinoflagellates</td>
</tr>
</tbody>
</table>

of maximum phytoplankton concentration, which was approximately at the depth of 1.5 m, on 22 April 2002. It was formulated as follows:
for extracted Chl $a$ concentration ranging between 8 and 73 mg m$^{-3}$, with an estimation error of Chl $a$ of <13.5 mg m$^{-3}$. For the mapping of the "surface" Chl $a$ when 	extit{P. gatunense} appeared we used the 1–3 m layer (Fig. 2(b)). The linear correlation between the concentration at that layer and the average value of the 0–10 m layer was higher than that of the 4–6 m ($r^2 = 0.87$, $n = 31$, $P < 0.0001$) and apparently better represented the lake epilimnion than the 0–1 m layer, which showed a correlation of 0.68. Analysis of the Lake Kinneret database for the years from 1988 to 1998 showed $r^2 = 0.80$ ($n = 46$, $P < 0.0001$), between the maximal Chl $a$ concentration and the total concentration in the 0–10 m uppermost water when 	extit{P. gatunense} dominates the lake phytoplankton. We therefore assume that using the maximum concentration values is an expedient approach for representation of the epilimnion, when dinoflagellates are the major component of the phytoplankton.

We analysed the results from 10 excursions that took place between June 2001 and April 2002 (Table 1). Despite the apparent patchiness of phytoplankton distribution throughout most of the surveys we did, the overall spatial variation was relatively low. Thus, for instance, in the map constructed from the data taken on 21 November 2001, there is a clear distinction of Chl $a$ concentration patches (Fig. 2(a)), but it should be noted that the entire range of Chl $a$ concentration is 6–12 mg m$^{-3}$. Our preliminary work with the Chinese sensor Feng Yeng 1c, with a spatial resolution of about 1.1 km, shows the feasibility of the remotely sensed information for mapping phytoplankton distribution at the lake surface (Blumberg, Natan and Yacobi, unpublished data), even if the range of phytoplankton concentrations was as low as indicated. In the past we could map phytoplankton distribution in the lake using satellite-carried sensor information when the range of Chl $a$ concentration was even lower, but based on the high degree of spatial resolution available in LandsAT images (Mayo et al., 1994).

The spatial homogenization of phytoplankton distribution is a well-known characteristic of Lake Kinneret phytoplankton in recent years and is primarily a consequence of the decline in concentrations of the dinoflagellate 	extit{P. gatunense}. In 2002 	extit{P. gatunense} reappeared, and is documented in the April experiment, in the relatively high chlorophyll concentrations as well as in relatively high spatial variability (Fig. 2(b)), but still far from the value seen in previous years.

The spatial distribution of the dominant phytoplankton group pretty much overlapped the distribution of Chl $a$ in the epilimnion, in each one of the surveys. The FP does not distinguish between diatoms and dinoflagellates, but that limitation can be resolved by other means (e.g. microscopy), as shown in Table 1.

**CONCLUSIONS**

In this work we demonstrated the use of a tool for a comprehensive mapping of phytoplankton and the contribution of its colour groups. The combination of measurements accomplished by the FP and data analysis utilizing the aid of GIS techniques, enable 3-D observations of the plankton and its components, a short time after data acquisition. The concentration of Chl $a$ measured by the FP in the uppermost layers during the daytime is not useful information for the goal of remote sensing calibration.
The variation introduced by the phenomenon of fluorescence quenching is time-dependent, as the intensity of quenching increases with the duration of exposure of phytoplankton cells to excessive light. Measurement at night-time is a solution for the problem, if phytoplankton mapping is the sole goal of the work. But, if the phytoplankton mapping is aimed as a ground-truth database for remotely operated sensors that collect passive light reflected from the water surface, then the solution is to use information derived from the water layer that resides beneath the depth when the fluorescence quenching occurs. In the case of Lake Kinneret that goal is mostly feasible, as the vertical distribution of phytoplankton is pretty uniform in the uppermost 0–10 m layer of the lake. If motile phytoplankton dominates the phytoplankton it is expedient to use the layer that includes the peak concentration to represent the Chl $a$ concentration at the surface, assuming that the reflectance emerging from the water surface is influenced by the phytoplankton density of the maximum chlorophyll layer, if it resides close to the surface.

REFERENCES


