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Determination of chlorophyll and dissolved organic carbon from reflectance data for Colorado reservoirs

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Abstract. Relationships between phytoplankton abundance, concentration of dissolved organic carbon (DOC), and reflectance spectra were investigated in eight reservoirs of the Colorado Front Range. The purposes of the study were: (1) to determine the degree to which chlorophyll and DOC could be determined from spectral data of the type that can be acquired through remote sensing; and (2) to determine whether equations developed for other waters are applicable to Colorado reservoirs. Supplementary information was obtained from water selectively enriched in dissolved organic carbon (Georgia blackwater lakes) and in phytoplankton (phytoplankton cultures). Reflectance for the lakes ranged from 1 to 5 per cent across the spectrum. All lakes showed a peak of reflectance near 570 nm (green range) corresponding to the minimum absorption for chlorophyll. For both the reservoirs and the phytoplankton cultures, a peak near the red-infrared boundary (*ca* 700 nm) increased in size and shifted toward longer wavelengths with increasing concentration of chlorophyll a. Georgia blackwater lakes dominated by DOC yielded flat spectra combined with low overall reflectance (usually below 1 per cent). With the presence of tripton in addition to DOC, reflectance was higher and showed peaks near 710 and 810 nm caused by selective scattering and absorption. For the eight reservoirs, chlorophyll showed a very close relationship to ratios of reflectance at a number of wavelengths. The strongest relationship was for the ratio of reflectance in the near-infrared to reflectance in the green spectral range ($r^2 = 0{\cdot}98$): Chlorophyll a, $\mu g\ l^{-1} = 407\ (R_{806}/R_{571})^{2{\cdot}52}$. Single ratios of reflectance did not show such strong relationships with concentrations of dissolved organic carbon ($r^2 < 0{\cdot}70$). Concentrations of DOC were related strongly, however, to dual ratios that were identified through multiple regression analysis. The closest relationship was ($r^2 = 0{\cdot}95$): DOC, $mg\ l^{-1} = 0{\cdot}55\ [(R_{716}/R_{670})^{-9{\cdot}60}][(R_{706}/R_{670})^{12{\cdot}94}]$. Reflectance ratios of red to green wavelengths and ratios containing reflectance near 800 nm work well for predictions of chlorophyll in Colorado reservoirs, although equations of this type have not been previously reported in the literature. Equations that have been developed for other areas do not consistently fit the data for Colorado reservoirs. Spectral analysis of reflectance in relation to water quality will be required from numerous geographic regions before universal equations or universal typologies can be considered.

1. Introduction

Concentrations of chlorophyll in water have been estimated from the spectral distribution of backscattered light (Gitelson *et al.* 1993 a, Kirk 1994); DOC and tripton have also been related to reflectance, but much less frequently. Remote sensing in general has been used much more extensively for oceans than for inland waters, especially those of small to moderate size. Whereas chlorophyll is typically the main constituent responsible for spatial and temporal variation in the reflectance

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spectrum of ocean waters, inland waters often contain amounts of dissolved organic carbon and non-living particulate matter (tripton) that make interpretation of the reflectance spectrum more difficult. Furthermore, the range of combinations for these factors varies regionally for inland waters.

A generalized reflectance profile (figure 1) shows the difficulties of working with inland waters. In particular, the overlap between phytoplankton and DOC signals is a major handicap in predicting the concentration of either of these components. DOC can originate not only from phytoplankton, but also from terrestrial vegetation via soils (Thurman 1985). Thus estimates of DOC concentration cannot be inferred from phytoplankton abundance, even though the two may be correlated.

The study described in this paper provides a regional analysis for reservoirs of the Colorado Front Range (figure 2). The analysis is based on spectral and water quality data for eight reservoirs, supplemented with spectral studies of water selectively enriched in phytoplankton or DOC. Because these reservoirs show minimal tripton, the focus of the analysis is on phytoplankton (chlorophyll) and DOC. Long wavelengths (>700 nm), which have been analysed much less thoroughly than wavelengths of the visible range, are included in the study. The aims of the study are: (1) to determine the degree to which chlorophyll and DOC could be determined from spectral data of the type that can be acquired through remote sensing; and (2) to determine whether equations developed for other waters are applicable to Colorado reservoirs.

2. Methods

The eight reservoirs, which vary in trophic state from oligotrophic to eutrophic, lie within a 100-km radius of Denver at an elevation of about 1600 m above sea level (figure 2). Light penetration and spectral reflectance were measured once for each of the eight reservoirs on cloudless days between 23 August and 16 October 1991, an interval when phytoplankton populations are expected to show considerable variation among lakes. Water samples for laboratory analysis were collected at the same time.

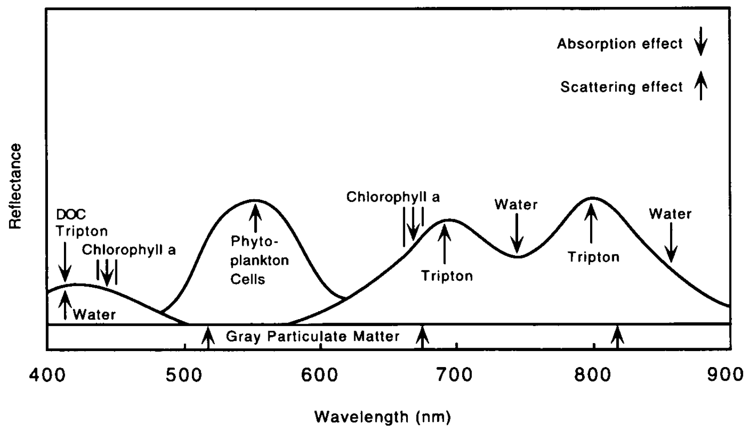


Figure 1. The generalized effects of chlorophyll a, dissolved organic carbon, and particulate matter on the reflectance spectrum of a hypothetical inland water body.

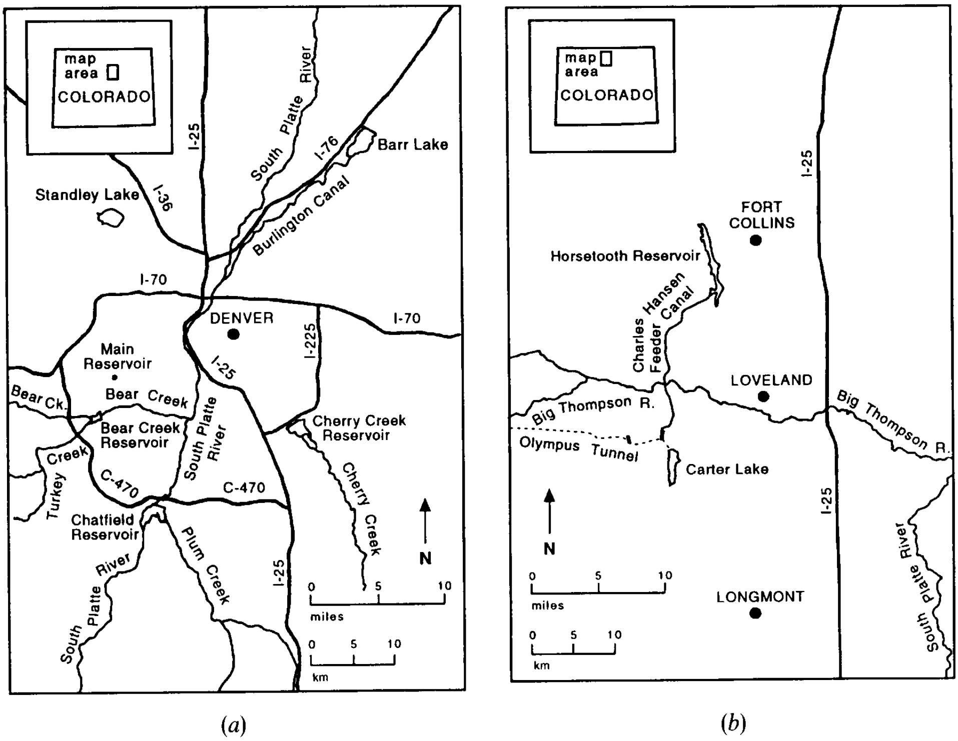


Figure 2. Location of Colorado Front Range reservoirs. (*a*) Sites near Denver, (*b*) sites near Fort Collins.

Particulate matter, which for these eight reservoirs consisted predominantly of phytoplankton cells, was collected on glass fibre filters (Whatman GF/C, effective pore size *ca.* 0·7 μm, Sheldon 1972). The filter was then analysed for organic carbon with an elemental analyser, and the filtrate was analysed for absorption with a scanning spectrophotometer (300–900 nm). Chlorophyll a was analysed by the spectrophotometric method of Marker *et al.* (1980) and Nusch (1980). Concentrations of dissolved organic carbon (DOC) were measured by gas chromatography (GC) following persulphate digestion (Lewis *et al.* 1986).

Phytoplankton sub-samples were taken from water samples of each reservoir. These samples were preserved with Lugol's solution and were counted with an inverted microscope (Lewis 1978). Bio-volume (volume occupied by living phytoplankton) was calculated for each sample.

For each reservoir, a vertical profile of light intensity was measured with a quantum sensor, and the light extinction coefficient was calculated from a semilogarithmic plot of quantum flux versus depth. Transparency was measured with a Secchi disc.

Water surface reflectance values for the full spectral range were collected approximately 1 m above the water surface with an ALEXA Spectrometer on the same day that light penetration measurements and water samples were obtained. Wave facets can affect readings at these distances; errors were minimized by the use of multiple readings. The ALEXA Spectrometer is a prototype of the Personal Spectrometer II, which is produced by Analytical Spectral Devices, Inc. of Boulder, Colorado. With each reading, the instrument records reflectance measurements at 512 wavelengths from a 15° field of view with a resolution of 4 nm. The spectral range of the instrument was 393–1075 nm, which was divided into 512 channels separated by 1·34 nm. Mean reflectances at each wavelength were calculated from three reflectance readings for each reservoir.

Certain wavelengths are of particular importance for analysis of reflectance: 445 and 665 nm are peaks of absorption for chlorophyll a, whereas 520 and 550 nm are minima for absorption by chlorophyll a (Zscheile and Comar 1941); these four wavelengths fall within the spectral sensitivity ranges of the Coastal Zone Color Scanner (Gordon and Morel 1983). Several ratios of these reflectances have been used in analysing data from CZCS and other sensors, and will also be used in this study: R_{440}/R_{520} (reflectance at 440 nm divided by reflectance at 520 nm), R_{440}/R_{550}, R_{550}/R_{520}, R_{670}/R_{520}, R_{670}/R_{550}.

The data from reservoirs were supplemented with data from waters dominated by a single component (phytoplankton or DOC). A study of phytoplankton (chlorophyll) was based upon a laboratory phytoplankton culture. Undiluted water from the culture was poured into a black (light-absorbing), 30-l container (depth, 1 m), which was placed in full sunlight on a cloudless day. Reflectance spectra were taken of the culture, then of progressive 50 per cent dilutions of the culture, and finally of deionized water. Mean reflectance values were calculated from five readings for each dilution. A spectrophotometer was used to measure absorption of the undiluted phytoplankton culture, as well as its filtrate and chlorophyll a extract. Concentration of chlorophyll a in the culture as also measured.

A supplementary study of DOC was performed with water from three locations in Georgia that were chosen because of their high DOC concentrations. Reflectance spectra were taken on a cloudless day from the edge of a bog that flows into Juniper Lake, near Columbus, Georgia. Spectra were also taken under similar conditions from Billys Lake in the Okefenokee Swamp near Fargo, Georgia, and from a dock that was connected to Billys Lake by a channel approximately 100 m long. Means of five reflectance values were calculated for each wavelength at each location. The water was also sampled at each site, subsamples were filtered (Whatman GF/C), particulate matter was weighed, and absorption profiles were measured for the filtrate (300–900 nm). Concentration of DOC was determined with a DOC analyser.

3. Results

Information on each of the reservoirs at the time of sampling is summarized in table 1. All of the variables showed a substantial range across the reservoirs, which is favourable for statistical analysis of relationships between reflectance and water quality. Relationships of the independent variables to each other were established by correlation analysis. To improve normality, all variables were transformed logarithmically prior to correlation analysis. The variables fall into three groups: (1) transparency (Secchi depth and extinction coefficient); (2) algal biomass (chlorophyll a, biovolume, particulate carbon); and (3) dissolved organic carbon. Variables within groups were strongly correlated to each other, as expected (table 2). Variables among groups were also correlated, but less strongly. Correlation of variables among groups illustrates the need to find distinctive reflectance features for each component that is to be predicted.

Reflectance ranged between 1 and 5 per cent across the spectrum for the eight lakes (figure 3). The spectra showed several common features. All had, as expected, a

Table 1. Physical characteristics and data on light penetration and water quality for Colorado Front Range reservoirs.

Reservoir	Surface elevation (m)	Mean depth (m)	Maximum area (km^2)	Extinction coefficient (m^{-1})	Secchi depth (m)	Chlorophyll a ($\mu g\, l^{-1}$)	Particulate carbon ($\mu g\, l^{-1}$)	Phytoplankton biovolume ($mm^3\, l^{-1}$)	DOC ($mg\, l^{-1}$)
Barr Lake	1550	5	7·60	1·55	1·20	62·6	3170	40·96	8·69
Bear Creek Reservoir	1730	8	5·01	1·00	1·75	11·7	1400	3·11	3·11
Carter Lake	1760	30	4·63	0·41	3·50	0·8	320	0·76	3·43
Chatfield Reservoir	1680	12	24·17	0·83	1·60	4·1	740	3·00	2·86
Cherry Creek Reservoir	1720	6	18·39	1·17	1·00	9·6	1160	7·61	6·34
Horsetooth Reservoir	1660	24	7·69	0·66	2·00	3·8	730	8·01	3·43
Main Reservoir	1720	3	0·24	0·84	1·80	10·1	1210	5·66	4·96
Standley Lake	1680	11	4·94	0·67	2·00	2·1	530	2·00	1·77

Table 2. Coefficients of correlation (r^2) between secchi depth, extinction coefficient, chlorophyll a, particulate carbon, phytoplankton biovolume, and dissolved organic carbon (all transformed by natural logarithms) for Colorado Front Range reservoirs. All correlations are significant at $p \leq 0.01$.

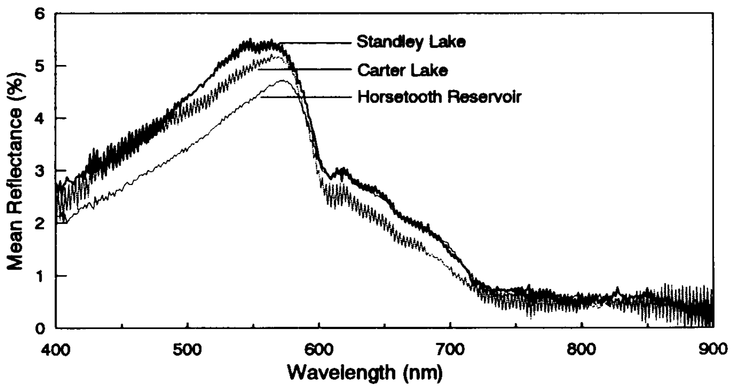
	Secchi depth	Extinction coefficient	Chlorophyll a	Particulate carbon	Phytoplankton biovolume	Dissolved organic carbon
Secchi depth	1·00	0·85	0·63	0·60	0·58	0·33
Extinction coefficient		1·00	0·91	0·90	0·71	0·43
Chlorophyll a			1·00	1·00	0·80	0·53
Particulate carbon				1·00	0·79	0·52
Phytoplankton biovolume					1·00	0·57
Dissolved organic carbon						1·00

peak in the green range (*ca.* 570 nm) corresponding to the spectral minimum for chlorophyll absorption. Peaks in the green spectral range typically rose gradually to a maximum at about 570 nm and fell sharply to about 600 nm. The reservoirs with least chlorophyll had the most sudden drop. With increasing amounts of algal biomass (chlorophyll a), reflectance generally: (1) decreased in the blue to green spectral region; (2) showed a smaller peak at green wavelengths; and (3) increased in the red to infrared range (especially near 700 nm). For the lakes rich in phytoplankton, a single peak of reflectance occurred near the red-infrared boundary; it shifted toward longer wavelengths with increasing concentrations of chlorophyll a.

Close relationships of variables within the phytoplankton group show that prediction of any one variable from the group will allow prediction of the other variables. The reflectance analysis is based on chlorophyll, but phytoplankton biovolume and particulate carbon can be estimated from chlorophyll as follows: Bio-volume ($mm^3\,l^{-1}$) = 0·63 (chlorophyll a, $\mu g\,l^{-1}$) + 0·60, Particulate carbon ($\mu g\,l^{-1}$) = 42 (chlorophyll a, $\mu g\,l^{-1}$) + 602.

Reflectance from the laboratory phytoplankton culture, dilutions of that culture, and deionized water ranged between 0·5 and 2·0 per cent (figure 4). Concentration of chlorophyll a was 171 $\mu g\,l^{-1}$ for the undiluted phytoplankton culture; this was much higher than for the reservoirs (table 1). Each succeeding dilution contained approximately half the concentration of the previous one. Progressively lower phytoplankton concentrations resulted in lower reflectances across the spectrum. Reflectance spectra of the undiluted phytoplankton culture and of the first few dilutions showed high reflectances in the green spectral range and a distinctive peak in the red to infrared spectral range. Reflectance spectra from dilutions containing chlorophyll concentrations of less than 20 $\mu g\,l^{-1}$ had poorly defined peaks, probably because of the large amount of light absorbed by the black container when the transparency of the water was high.

Data from blackwater lakes in Georgia are summarized in figure 5. Billys Lake contains DOC but no significant amounts of phytoplankton or tripton. DOC concentration was very high, as was absorption in the blue range. Filtration did not change the absorption spectrum because of the virtual absence of particulate matter. Billys Lake had a flat reflectance spectrum, low reflectance values (generally <1 per cent), and appeared very dark blue (close to black), which indicated that absorption by



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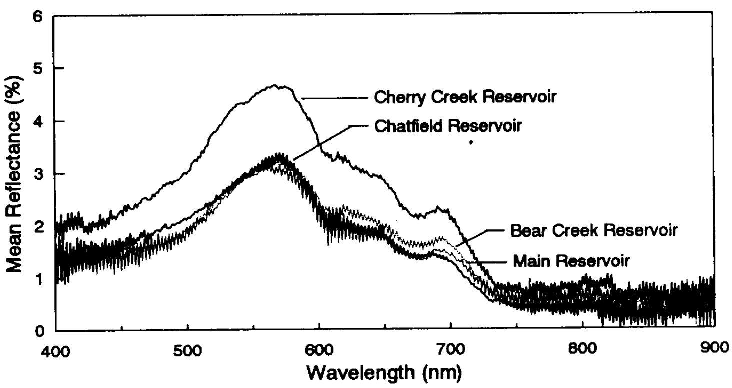

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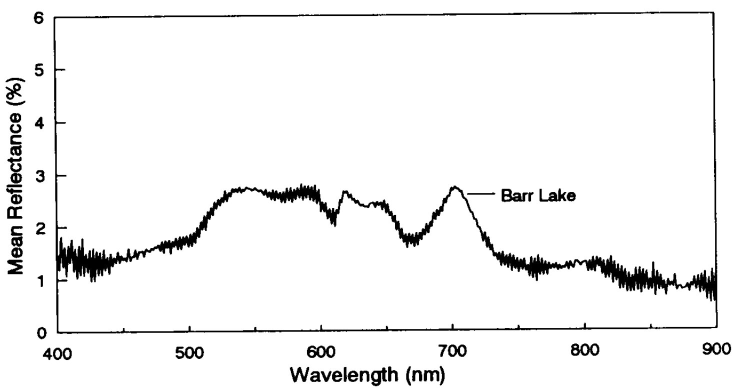

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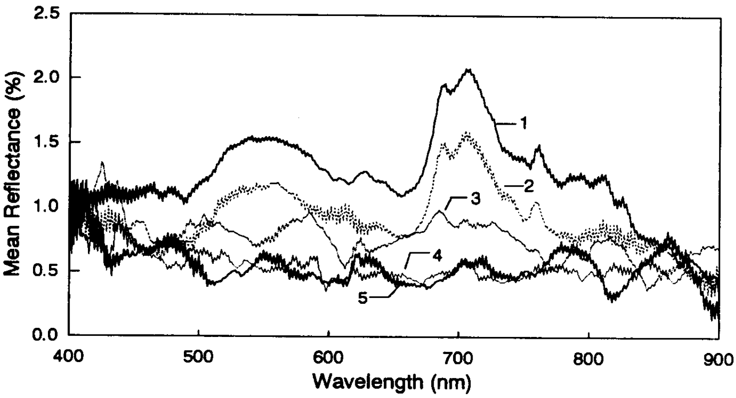
Figure 3. Mean reflectance for Colorado Front Range reservoirs grouped according to shape of spectrum (*a*) = lowest chlorophyll, (*b*) = intermediate chlorophyll, (*c*) = highest chlorophyll.



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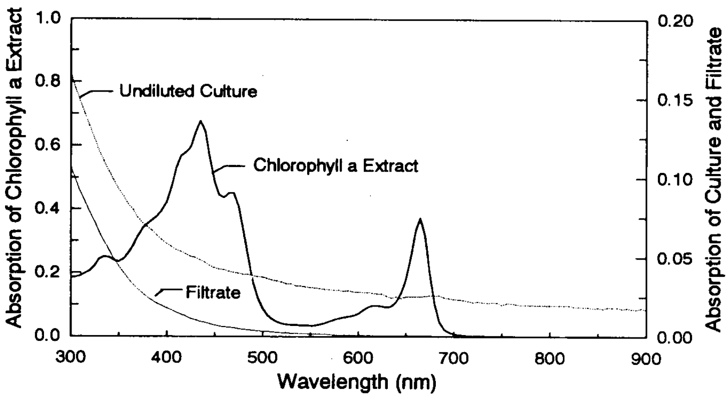


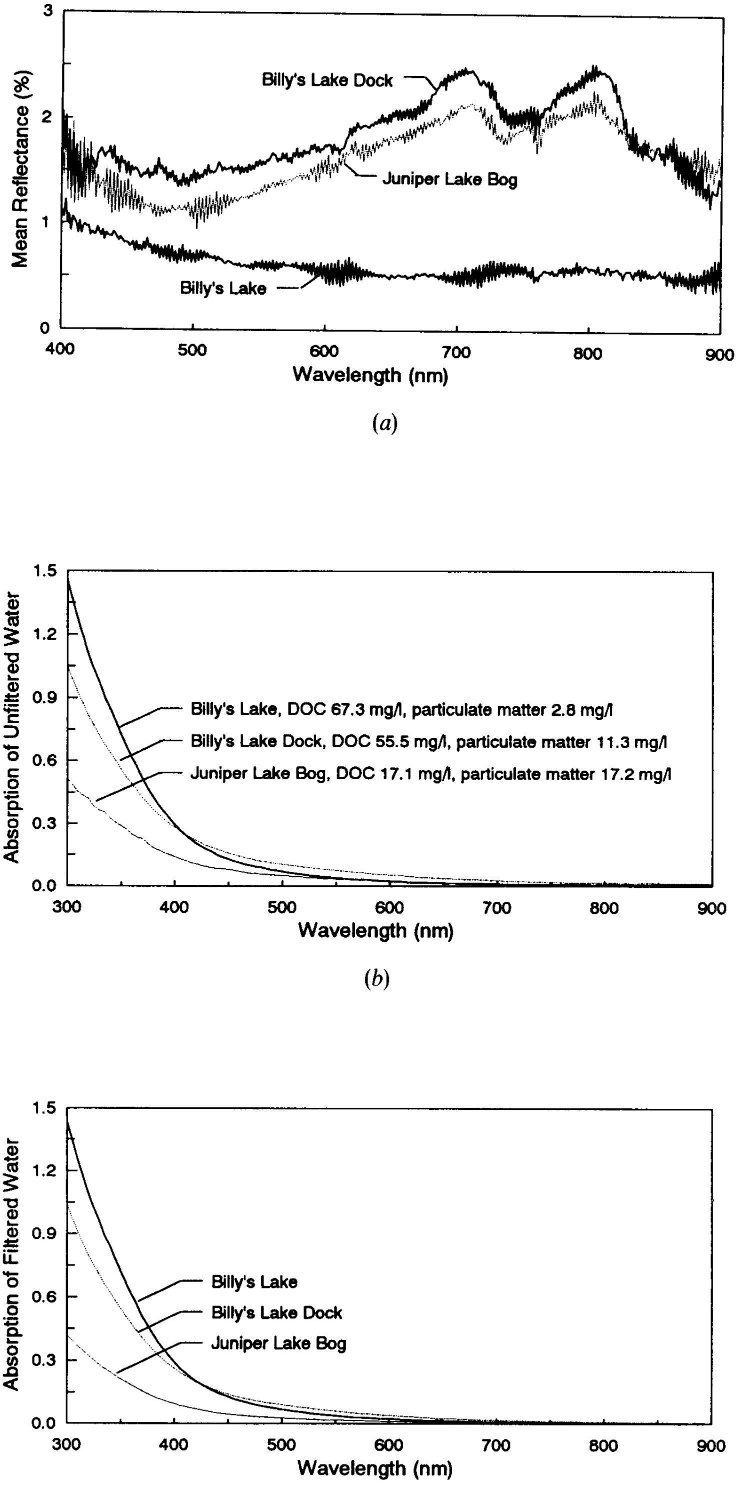
(*b*)

Figure 4. Reflectance and absorption spectra for a phytoplankton culture. (*a*) Reflectance spectra for the undiluted phytoplankton culture (1), progressive 50 per cent dilutions (2–4), and for deionized water (5). (*b*) Absorption spectra (1 cm pathlength) for the undiluted phytoplankton culture, chlorophyll a extracted from the culture (in 90 per cent ethanol), and filtered water from the culture.

DOC had a strong effect on reflectance across the spectrum, as suggested by Witte *et al.* (1982).

Water at the Billys Lake dock was high in DOC, but also contained some tripton, in contrast to the water from Billys Lake. Reflectance spectra show peaks near 710 and 810 nm, which were caused by tripton. The absorption of light in filtered water was lower than in unfiltered water because of the presence of tripton. Absorption curves from unfiltered and filtered water were similarly shaped with no noticeable peaks (*cf.* Davies-Colley 1983, Howard-Williams and Vincent 1985).

Juniper Lake bog had high absorption in the blue range, high DOC, and the highest ratio of tripton to DOC. Reflectance peaks near 710 and 810 nm indicate scattering. The presence of tripton explains not only scattering, but also the difference in absorption between unfiltered and filtered water. The peaks of reflectance are similar to but less pronounced than those of Billys Lake dock.



(c)

Figure 5. Reflectance and absorption spectra for Georgia lakes.

4. Data analysis

4.1. *Analysis of single reflectances and single reflectance ratios*

Many investigators have used ratios of reflectance in two bands to predict chlorophyll (Gordon *et al.* 1980). The use of ratios is one way of minimizing overlapping spectral effects for different substances, and may also mask certain atmospheric effects (Dekker 1993). Ideally, a spectral reflectance ratio should contain one wavelength corresponding to high reflectance and the other to high absorption for the substance of interest. Ratios involving more than two wavelengths are also possible, but can be affected adversely by cumulative variance.

For the eight Colorado reservoirs, reflectance was regressed against concentration of chlorophyll a and DOC at all wavelengths (all variables logarithmically transformed). The purpose of this step in the analysis was to show the wavelengths that might be most useful in wavelength ratios. Consideration of correlations at all wavelengths is a commonly used method for screening statistical relationships that may have predictive power (Lewis and Tyburczy 1974, Vertucci and Likens 1989, Dekker 1993, Gitelson *et al.* 1993 a). The r^2 values for chlorophyll (0·5–0·70) were higher than those for DOC (0·20–0·35) in the blue and green ranges of the spectrum (figure 6). Both chlorophyll and DOC showed very low values in the red ($<0·05$), and relatively high values in the near-infrared (0·60–0·90). The r^2 values peaked between 440 and 510 nm, at 571 nm (the approximate peak reflectance for most of the reservoirs), and in the near-infrared spectral range at 716 and 806 nm.

Reflectances at 440 and 670 nm (wavelengths of maximum light absorption by chlorophyll), 700 nm (maximum spectral shift with chlorophyll), and at 571, 716, and 806 nm (wavelengths of highest r^2) were subjected to further analysis. The logarithms of ratios of these reflectances were regressed with the logarithms of concentrations for chlorophyll and DOC (figure 6). Overall, the wavelengths showing high r^2 values as numerators of ratios (571, 716, and 806 nm) also produced the highest r^2 values in the analysis of individual reflectances. Ratios incorporating the wavelengths of chlorophyll absorption maxima (440, 670 nm), however, did not show such high r^2 values.

4.2. *Equations relating reflectance to chlorophyll a and DOC*

The equations most closely relating reflectance to the concentration of chlorophyll a (indicated by $r^2 \geq 0·95$, table 3) involve ratios of reflectance at near-infrared wavelengths (increased reflectance for reservoirs of higher trophic status) over reflectance at green wavelengths (high reflectance in the visible wavelength range for all reservoirs, and declining reflectance with higher trophic status). Equations containing reflectance ratios of infrared to red wavelengths (maximum chlorophyll a absorption at longer visible wavelengths) are also useful for predicting chlorophyll a ($r^2 = 0·89$–$0·93$).

DOC concentration is less closely related to single reflectances or single reflectance ratios than chlorophyll a. As shown in table 3, the best equation for predicting DOC from single reflectances in Colorado Front Range reservoirs has an r^2 of 0·60 and the best equation for DOC involving a ratio has an r^2 of 0·62. Because r^2 values from simple regressions involving dissolved organic carbon concentration were well below 0·90, in contrast to those for chlorophyll, multiple regression models were developed for the relationship of DOC with combinations of reflectances at 440, 520, 550, 571, 670, 700, 716 and 806 nm. Reflectance ratios that produced significant r^2 values in simple linear regression models (table 3) were used as the first independent variable in each multiple regression. Even though they produced no significant r^2

values for simple linear regressions, reflectance ratios with 670 nm in the numerator were also used because of the high absorption of chlorophyll and lower absorption by other components at this wavelength. The second independent variable for each regression consisted of a ratio with: (1) the same reflectance in the denominator as for the first independent variable; and (2) numerators consisting of reflectance at each wavelength across the spectrum.

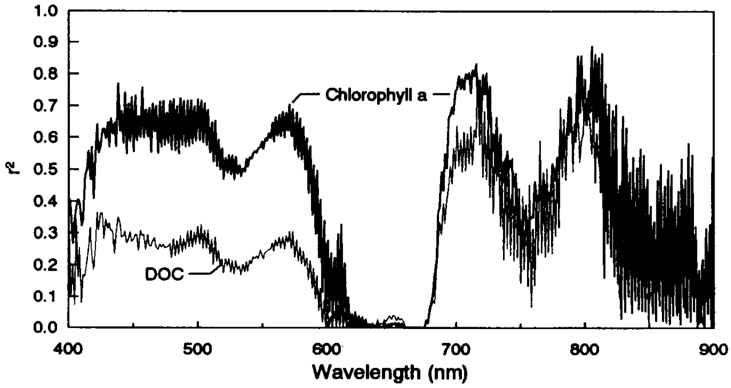
The best multiple regressions for DOC resulted in r^2 values of 0·70–0·95 (table 4). This indicated a considerably stronger potential for predicting DOC from equations developed from multiple regression models than from those developed from simple regression models. Regressions with the highest r^2 (0·84–0·95) involve reflectance ratios with 670, 700, and 716 nm in the numerator of the first independent variable. Other equations with ratios of reflectance at near-infrared to red wavelengths in both independent variables had r^2 values of 0·85–0·86. Equations with ratios of reflectance at near-infrared to green wavelengths in both independent variables were also useful for predicting DOC concentration. Other equations with ratios of reflectance at near-infrared to green wavelengths resulted in regressions with r^2 between 0·84 and 0·89. Equations with ratios of reflectance at red and green wavelengths in the first independent variable showed high r^2 (0·93). Other strong relationships of DOC with ratios of red to green wavelengths in the first independent variable had r^2 values between 0·85 and 0·89. In addition, DOC is strongly related to ratios of blue and green wavelength in the first independent variable ($r^2 = 0{\cdot}90$).

5. Discussion

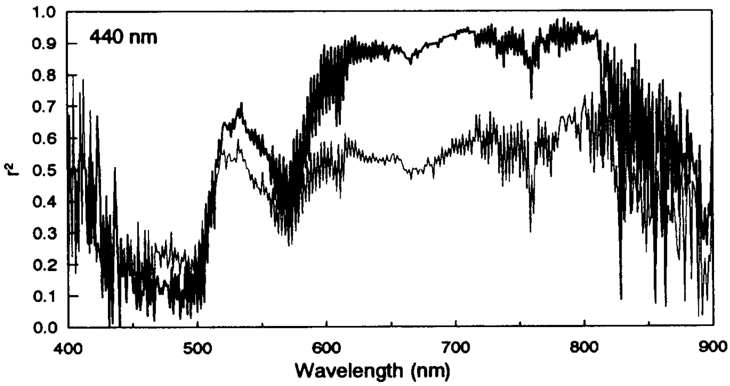
5.1. *Chlorophyll a*

The reflectance spectra from Colorado Front Range reservoirs (figure 3) are generally similar in shape to those from many other lakes of similar trophic range. High reflectances between 500 to 600 nm are probably explained by chlorophyll a absorption at these wavelengths coupled with high backscattering caused by algal cells (Dekker 1991, 1993). The strong influence of chlorophyll on reflectance in this range is confirmed by similar peaks ranging from 520 to 590 nm in reflectance spectra from the laboratory culture containing high concentrations of phytoplankton (figure 4). For the reservoirs, the trend toward decreasing reflectances with increasing chlorophyll was opposite to the trend for the laboratory phytoplankton culture as well as lakes in a number of other locations. For example in Lake Kinneret, Israel, Gitelson *et al.* (1993 b) showed a direct relationship between reflectance and concentration of chlorophyll a.

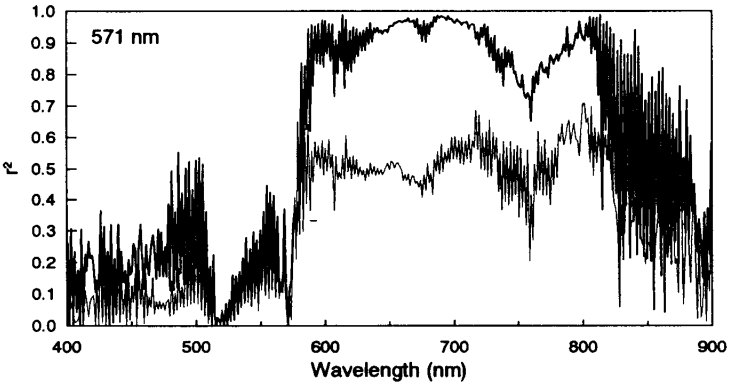
High reflectances in the red-infrared range among Colorado Front Range reservoirs are similar to those from the laboratory phytoplankton culture (figure 4) and those obtained by other researchers (Kishino *et al.* 1986, Davies-Colley *et al.* 1988, Gitelson 1992). These peaks can be explained by one or a combination of three processes; chlorophyll fluorescence at wavelengths longer than the 670 nm absorption peak, minimum values for the combined absorption curves by algae and water, and scattering at wavelengths longer than 670 nm (Morel and Prieur 1977, Gordon 1979, Vasil'Kov and Kopelevich 1982, Carder and Steward 1985, Vos *et al.* 1986, Hoge and Swift 1987, Gitelson and Kondratyev 1991, Dekker 1993). Gitelson *et al.* (1993 a) illustrated a similar reflectance gradient between red and infrared wavelengths with data from various locations in Lake Balaton, Hungary, in which chlorophyll concentrations were correlated with peaks due to sun-induced fluorescence that increased in magnitude and shifted spectrally between 685 and 705 nm.


Chlorophyll a
DOC
r²
Wavelength (nm)

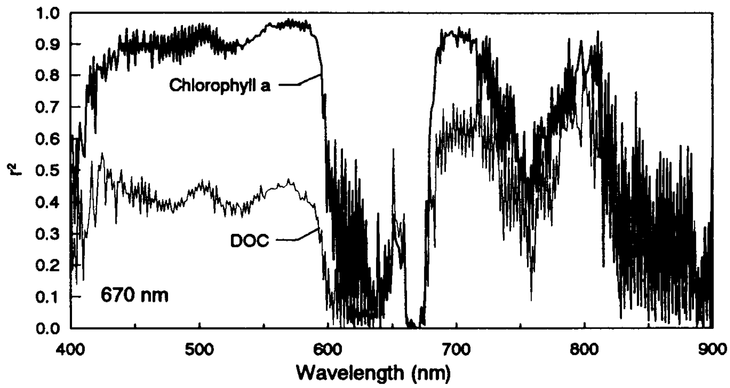
(a)


440 nm
r²
Wavelength (nm)

(b)


571 nm
r²
Wavelength (nm)

(c)



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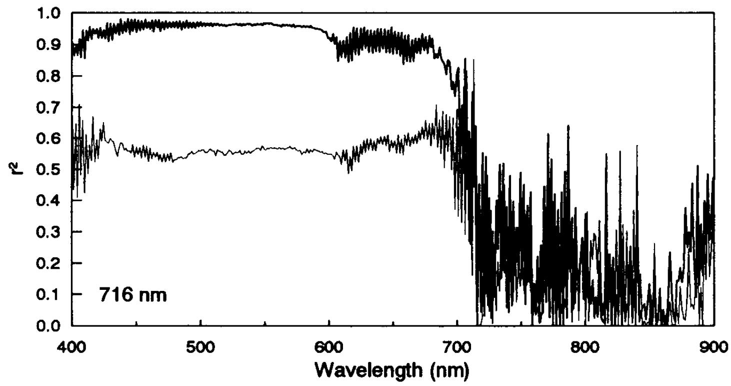

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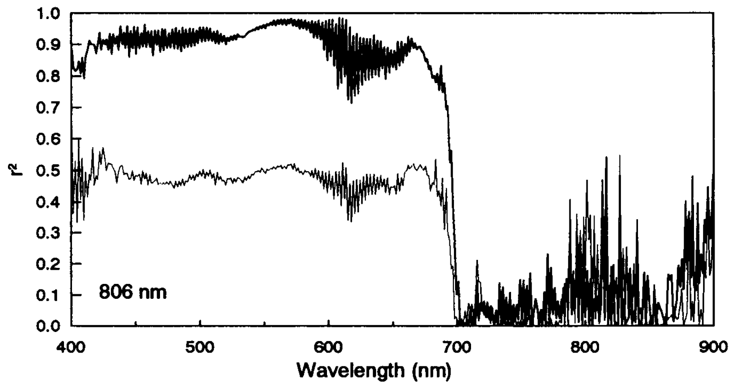

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Figure 6. (*a*) Correlations between chlorophyll a concentration and reflectance, and between dissolved organic carbon concentration and reflectance, for Colorado Front Range reservoirs. Each r^2 value is calculated from mean reflectance values at the measured wavelength. All concentrations and reflectances are transformed by natural logarithms. (*b–f*) Correlations between concentration of chlorophyll a and selected reflectance ratios, and between concentration of dissolved organic carbon and selected reflectance ratios, for Colorado Front Range reservoirs.

Table 3. Relationships of chlorophyll a and dissolved organic carbon to selected reflectances and reflectance ratios for Colorado Front Range reservoirs.

Independent variable	Chlorophyll a ($\mu g l^{-1}$)			DOC ($mg l^{-1}$)		
	Coefficient	Exponent	r^2	Coefficient	Exponent	r^2
440	$5{\cdot}26\times10^{-4}$	−2·35	0·62*	0·29	−0·65	0·33
520	$2{\cdot}36\times10^{-4}$	−2·93	0·47	0·38	−0·67	0·17
550	$2{\cdot}10\times10^{-5}$	−3·81	0·59*	0·20	−0·91	0·23
571	$1{\cdot}59\times10^{-5}$	−3·94	0·70**	0·16	−0·98	0·31
670	1·97	−0·28	0·00	5·21	0·07	0·00
700	$1{\cdot}03\times10^{8}$	4·02	0·75**	678·58	1·25	0·50*
716	$2{\cdot}23\times10^{7}$	3·34	0·83**	487·85	1·07	0·60*
806	6.03×10^{9}	4·20	0·89**	1808·04	1·24	0·55
440/520	0·27	−6·16	0·63*	1·30	−2·16	0·55*
440/550	0·21	−4·94	0·54*	1·28	−1·64	0·42
440/571	0·41	−3·79	0·32	1·57	1·27	0·25
550/520	4·14	2·19	0·01	3·82	0·09	0·00
571/520	9·68	−2·32	0·04	4·71	−0·96	0·05
571/550	9·30	−12·26	0·30	4·44	−3·89	0·21
670/520	129·02	5.45	0·85**	8·17	1·32	0·35
670/550	601·85	6·31	0·95**	12·30	1·59	0·42
670/571	387·61	5·44	0·95**	11·47	1.42	0·45
700/520	39·25	2·76	0·96**	6·42	0·75	0·50*
700/550	68·03	2·87	0·97**	7·61	0·79	0·53*
700/571	62·18	2·65	0·97**	7·46	0·74	0·53*
700/670	10·70	4·90	0·93**	4·57	1·46	0·58*
716/520	71·52	2·34	0·96**	7·85	0·67	0·55*
716/550	114·43	2·40	0·97**	9·03	0·69	0·57*
716/571	101·49	2·24	0·96**	8·76	0·65	0·57*
716/670	36·60	3·64	0·92**	6·75	1·13	0·62*
806/520	212·72	2·42	0·90**	10·07	0·65	0·45
806/550	450·34	2·63	0·96**	12·55	0·71	0·50*
806/571	407·48	2·52	0·98**	12·30	0·69	0·52*
806/670	259·82	4·14	0·89**	11·36	1·18	0·51*

* r^2 significant at $p \le 0{\cdot}05$.
** r^2 significant at $p \le 0{\cdot}01$.

The strongest relationship of chlorophyll a to reflectance or fluorescence occurred with ratios at near-infrared wavelengths over green wavelengths (table 3). High reflectances occur in the green range, which is a minimum for absorption by chlorophyll a, and low reflectances occur in the near-infrared range by wavelengths of low absorption by water. These equations are similar to the ones developed by Gitelson (Gitelson and Keydan 1990, Gitelson 1992, Gitelson *et al.* 1993 a), who showed that reflectance ratios of R_{700}/R_{560} and R_{695}/R_{573} were closely related to concentration of chlorophyll a (table 5). In addition, Mittenzwey *et al.* (1988) predicted chlorophyll in mesotrophic to eutrophic waters with a binomial equation containing the ratio R_{705}/R_{550}.

Chlorophyll concentrations in Colorado reservoirs are also closely related to ratios of reflectances at infrared to red wavelengths (table 3). These results are consistent with those of Dekker *et al.* (1989) who, after studying eutrophic lakes that were high in algae, DOC, and organic detritus, noted that the best estimations of water quality can be made from ratios of wavelength bands between 600 and 720 nm.

Table 4. Relationships of dissolved organic carbon to selected pairs of reflectance ratios for Colorado Front Range reservoirs. All r^2 values are significant at $p \leq 0.05$.

First ratio	Second ratio	Coefficient	First exponent	Second exponent	r^2
440/520	403/520	0·13	−4·12	−2·54	0·90**
670/520	501/520	0·28	−1·81	−10·05	0·76
670/520	717/520	6·36	−2·39	1·80	0·82**
670/520	800/520	14·88	−2·43	1·84	0·85**
670/550	622/550	0·53	−8·78	12·34	0·76
670/550	698/550	1·42	−4·98	3·19	0·80
670/550	717/550	5·58	−2·46	1·82	0·82**
670/550	778/550	9·39	−4·95	2·26	0·89**
670/550	800/550	13·33	−2·31	1·79	0·84**
670/550	807/550	12·06	−1·54	1·18	0·79
670/571	587/571	1·14	−4·66	25·46	0·88**
670/571	617/571	1·90	−4·90	8·01	0·82**
670/571	717/571	5·58	−2·58	1·91	0·82**
670/571	788/571	11·13	−5·69	2·66	0·93**
670/571	802/571	11·02	−2·50	1·50	0·85**
700/520	717/520	15·18	−2·07	2·71	0·82**
700/520	802/520	20·49	−0·77	1·23	0·78
700/550	717/550	17·46	−2·03	2·72	0·85**
700/550	800/500	41·68	−1·42	2·19	0·83**
700/571	717/571	17·12	−2·06	2·69	0·76
700/571	800/571	39·65	−1·45	2·16	0·82**
700/670	717/670	10·59	−1·31	2·52	0·85**
700/670	800/670	23·10	−0·71	2·06	0·85**
716/520	708/520	28·22	7·49	−7·35	0·82**
716/520	802/520	17·64	−0·67	1·25	0·77
716/520	807/520	18·73	−0·70	1·33	0·78
716/550	706/550	1·01	−13·16	15·60	0·92**
716/550	800/550	40·85	−1·58	2·63	0·84**
716/571	706/571	1·05	−12·33	14·50	0·89**
716/571	800/571	40·04	−1·67	2·65	0·84**
716/670	594/670	1·48	2·02	3·47	0·74
716/670	617/670	1·97	1·53	3·73	0·76
716/670	684/670	9·78	2·13	−4·42	0·77
716/670	706/670	0·55	−9·60	12·94	0·95**
716/670	737/670	3·13	2·02	−1·15	0·74
716/670	800/670	21·98	−0·76	2·33	0·86**
806/520	501/520	0·07	−1·26	−13·41	0·78
806/520	717/520	5·00	−1·26	2·07	0·79
806/620	820/520	12·94	0·22	0·48	0·72
806/550	717/550	6·55	−1·01	1·84	0·78
806/550	820/550	15·03	−0·30	0·43	0·72
806/550	832/550	8·25	2·02	−1·33	0·71
806/571	582/571	5·05	−0·19	16·35	0·75
806/571	717/571	6·49	−0·91	1·66	0·75
805/571	832/571	8·17	1·96	−1·31	0·72
806/670	618/670	5·70	1·27	2·55	0·70
806/670	698/670	1·67	−1·27	3·31	0·77
806/670	717/670	5·75	−0·55	1·94	0·82**
806/670	832/670	7·69	1·74	−1·53	0·79

** r^2 significant at $p \leq 0.01$.

Table 5. Relationships from the literature for predicting concentration of cholorophyll a ($\mu g\,l^{-1}$) and dissolved organic carbon ($mg\,l^{-1}$) from single reflectance ratios for lakes. All relationships were developed from data transformed by natural logorithms. (Sources: Gitelson and Keydan 1990, Gitelson *et al.* 1993 a, Vertucci and Likens 1989.)

Ratio	Coefficient	Exponent	Reference	Data sources	r^2
Chlorophyll a ($\mu g\,l^{-1}$)					
700/560	66	2·80	1	3 water bodies	0·88
700/560	123	2·30	1	Lake Balaton*	0·96
700/560	217	1·84	2	Lake Muggelsee*	0·90
700/560	67	2·84	2	River Don*	0·94
700/560	59	2·25	2	River Donec*	0·96
700/675	16	2·95	2	Lake Balaton*	0·92
700/675	56	1·75	2	Lake Muggelsee*	0·96
700/675	12	3·10	2	River Don*	0·92
700/675	13	3·05	2	River Donec*	0·96
477/700	2·5	−1·00	3	44 lakes	0·62
554/589	2·0	4·89	3	44 lakes	0·64
525/554	0·9	−5·86	3	44 lakes	0·77
445/554	0·88	−1·59	3	44 lakes	0·54
Dissolved Organic Carbon ($mg\,l^{-1}$)					
493/684	3·8	−0·39	3	44 lakes	0·78
589/620	4·8	−1·39	3	44 lakes	0·80

* This is the best of two or more equations for this wavelength ratio in this study.

Chlorophyll concentration has been predicted with R_{706}/R_{676} (Dekker 1993) and R_{700}/R_{675} (Gitelson *et al.* 1993 a) (table 5), which are similar to reflectance ratios that provide good estimates of chlorophyll in Colorado reservoirs. Also, in lakes that varied widely in trophic status, Mittenzwey *et al.* (1988, 1992) found that R_{705}/R_{670} was the most useful of several ratios.

Opportunities for predicting chlorophyll have not been exhausted. For example, chlorophyll has not been predicted previously from ratios of reflectance at red wavelengths over reflectance at green wavelengths, even though these ratios work well for Colorado reservoirs. In addition, equations with ratios incorporating reflectance near 800 nm are not given in the literature, although they perform well for Colorado reservoirs.

Equations that predict chlorophyll in one region may not necessarily work for another region. Although chlorophyll concentration has been predicted successfully with R_{520}/R_{550} (Melack and Pilorz 1990, Gitelson *et al.* 1993 a), this ratio is extremely unfavourable for predicting chlorophyll in Colorado Front Range reservoirs (table 3). In addition, none of the equations derived by Vertucci and Likens (1989), which contain the reflectance ratios R_{445}/R_{554}, R_{525}/R_{554}, R_{554}/R_{589}, and R_{477}/R_{700}, are useful for predicting chlorophyll a in Colorado Front Range reservoirs.

5.2. *Dissolved organic carbon (DOC)*

The literature contains very few equations for predicting DOC from reflectance data, and none containing ratios similar to the ones that are most effective for Colorado reservoirs. For example, Vertucci and Likens (1989) developed equations using R_{493}/R_{684} and R_{589}/R_{620} to predict DOC in the Adirondack mountain lakes (table 5). Their equations are not useful for predicting DOC concentration in the Colorado Front Range reservoirs, however.

DOC absorbs light across the spectrum that might otherwise have been backscattered, thus reducing the potential for reflectance (Witte *et al.* 1982). Also, DOC itself produces no significant scattering (Krijgsman, in preparation; cited in Dekker 1993). Thus a water column with DOC as the only primary component reflects very little light, and the reflectance is nearly uniform across the spectrum. This principle is confirmed by the data for Billys Lake (figure 5).

Absorption by DOC reduces reflectance across the spectrum for water containing DOC and tripton. Witte *et al.* (1982) showed that higher DOC concentrations correspond to a considerable decrease in reflectance at 550 and 650 nm, and a slight decrease at 750 nm. The decrease in reflectance at the green and blue wavelengths is greatest at low DOC concentrations, and absorption increases greatly at 550 nm but only slightly at 650 and 750. Witte *et al.* (1982) also showed that DOC increased absorption (particularly at blue wavelengths) and decreased reflectance across the visible spectrum in five Georgia rivers with significant amounts of tripton.

Water containing both DOC and tripton, such as that from the Billys Lake dock and the Juniper Lake bog, reflect light primarily in the red and infrared regions. High red and infrared reflectance from waters containing both DOC and particulate matter is explained by a combination of scattering from tripton and selective absorption by DOC at short wavelengths. In mesotrophic and eutrophic waters that contain primarily algae and DOC, some of the backscattered light from algal particulate matter may be absorbed by DOC, particularly in the ultraviolet to blue spectral range. This would increase the proportion of red and infrared light in the reflectance signal, as shown in the results from the Colorado reservoirs.

Scattering by tripton occurs across the spectrum and is particularly strong in the red to infrared spectral range, where tripton absorbs proportionally less than in the ultraviolet to blue range (Nova *et al.* 1989 a, b, Chen *et al.* 1991). Also, humic substances can be adsorbed by tripton (Greenland 1971, Davis 1980, Davies-Colley 1983). The adsorbed fraction of humic substances is in chemical equilibrium with DOC. The carbon-coated particles absorb exponentially into the blue-ultraviolet spectral range in a similar manner to DOC, thus increasing relative reflectance of red and infrared light. Because of these factors, light in a water column containing both DOC and tripton may be: (1) differentially backscattered from tripton, causing enrichment of reflectance in the red spectral range; (2) differentially absorbed on a tripton particle coated with DOC, causing suppression of blue and green light; and (3) absorbed by DOC at short wavelengths following backscattering. All three of these factors result in enrichment of the spectrum in the red spectral range.

The good performance of DOC equations involving wavelengths above 650 nm is unexpected because of the weak absorption of DOC above 650 nm. Witte *et al.* (1982) have documented a similar phenomenon, however. The utility of high wavelengths for prediction may lie in the interaction between DOC and tripton, which is not yet well understood.

6. Conclusions

Reflectance spectra from the eight Colorado reservoirs (figure 2) were similar in shape to spectra for some other locations (e.g., Dekker 1993), but not for all other locations (e.g., Vertucci and Likens 1989). In addition, comparison of predictive equations among sites (tables 3 and 5) shows that some equations are far more stable than others across sites, and that DOC equations are particularly variable and poorly documented. Confident use of equations across different regions will require more inter-regional comparisons, especially for DOC. These incongruities illustrate that classifications cannot be used outside specific regions unless they are drawn from a geographically diverse data base.

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