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RETRIEVAL OF CHLOROPHYLL *a* CONCENTRATION IN CASE 2 WATER BY USING SeaWiFS AND FIELD SPECTRORADIOMETER DATA

By

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SYNOPSIS

This paper examines a technique for retrieving chlorophyll *a* concentration by using field spectroradiometer data with fluorometer data and the Sea-viewing Wide Field-of-view Sensor (SeaWiFS) data. Spectroradiometer data were coupled with fluorometer data to find out the best suited bands ratio to monitor the chlorophyll *a* concentration for inland water. Remote sensing reflectance measurements were used to evaluate the performance of several default ocean color chlorophyll algorithms for SeaWiFS data. Remote sensing reflectance data from a spectroradiometer and *in situ* chlorophyll *a* data from a fluorometer were collected for Lake Abashiri, and SeaWiFS data for Lake Saroma were used. It was found that the chlorophyll *a* concentration from fluorometer and reflectance from spectroradiometer lies in exploiting the signal provided by the chlorophyll *a* red absorption peak near 670nm. The proposed estimation model based on two-band ratio of reflectance 670 and 700nm provided a good correlation for *in situ* chlorophyll *a*, compared with blue-green two-band ratio model.

INTRODUCTION

There has been considerable success in optical remote sensing of chlorophyll *a* in case 1 water (offshore water), where the variation of optical properties is dominated by phytoplankton and associated materials, and some consensus is emerging with regard to appropriate algorithms. In contrast, chlorophyll *a* retrieval in case 2 water (inland and seashore water), where the optical properties of inorganic suspended matter and colored dissolved organic matter from surface runoff must also be considered, is still a matter of intense research activity, and a few convincing examples are available of satellite-derived chlorophyll *a* concentrations for such water (Kishino et al (4); Ruddic et al (8)). However, the demand for detailed monitoring of chlorophyll *a* concentration in case 2 water is very high because of the need to manage the eutrophication at inland and coastal waters. Estuarine and coastal phytoplankton is important for atmospheric carbon dioxide and hence may affect climate change.

Stream ecosystems around the world are being impacted by the eutrophication. The eutrophication is the state of having high nutrient content and high organic production (Wetzel (11)). Most water quality models simulate an increase in eutrophication based on initial and boundary conditions of the water body, therefore, which demand the comprehensive water quality sampling programs. However, the conventional measurement of water quality requires *in situ* sampling, time-consuming laboratory work and a lot of expenses. Due to these limitations, the spatial and temporal sample size is not often large enough to cover the entire water body. Therefore, difficulties related to synoptic and successive water sampling become a barrier to water quality monitoring and forecasting. Remote sensing can overcome these constraints by providing an alternative means of water quality monitoring over a range of temporal and spatial scale. Hence, imagery from satellite and aircraft remote sensing systems have been used to assess water quality parameters such as temperature, chlorophyll *a*, turbidity, and total suspended solids for lakes, reservoirs and coastal waters (Lathrop and Lillesand (5), Lillesand et al (6) and Ruiz-Azuara (9)).

In this study, SeaWiFS data was used to view and check the validity of the algorithms for inland water chlorophyll *a* concentration in Lake Saroma, Hokkaido, Japan. Using the default chlorophyll algorithms used in TeraScan System (OC2-V2) and SeaDAS (OC4-V4) as the basis of comparisoning, we examined the validity of these empirical chlorophyll algorithms with *in situ* data. Spectroradiometer and fluorometer data were collected for Lake Abashiri, Hokkaido, Japan. These data sets were also used to check the validity of the derived chlorophyll algorithms by using the same band ratio of SeaWiFS, and finally organized the data sets to determine the correlation between spectral index and chlorophyll a concentration.

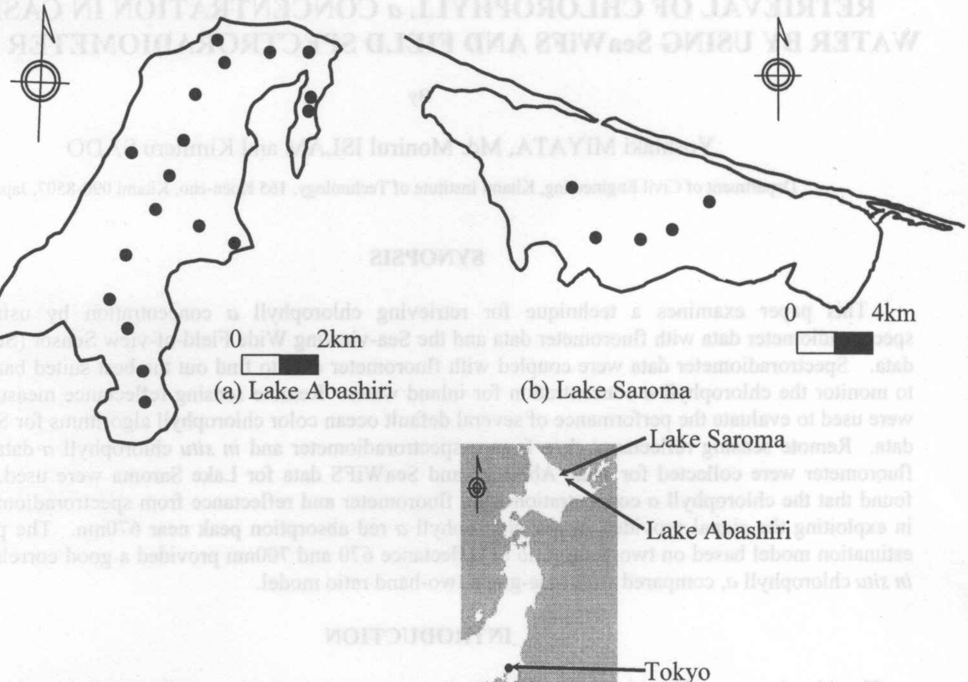


Fig. 1 Selected study areas

STUDY AREA

The study sites are Lake Abashiri and Saroma, located in Hokkaido, Japan. Lake Saroma is the third largest lake in Japan and the largest in Hokkaido. Both lakes are famous for tourist resorts and Saroma Lake has the largest haul of scallop culture in Japan. However, sometimes water blooms often occur in these lakes. Nowadays the water of these lakes are polluted by river waters that contain contaminated matters from the sewage and farmland. Therefore, the water quality monitoring of these lakes has become a matter of important concern. The selected study areas are shown in Figure1.

DATA COLLECTION AND PREPARATION

Fluorometer data for *in situ* measurements of chlorophyll a and spectroradiometer data for reflectance measurements were collected from May to October in the year of 1997 to 2000 for different stations (the stations are shown in Figure 1 (a)) in Lake Abashiri. Initially, the data was sorted for good quality for spectral data based on the spectral quality for radiation measurements. After sorting, the total of 49 data were used in this study. The spectroradiometer data set ranges from 350 to 900nm by the resolution of 1nm. The spectroradiometer data set was accompanied by Secchi disk data and fluorometer data for chlorophyll a, turbidity, temperature in different water depths. Water transparencies were measured by using Secchi disk depth. The averaged chlorophyll a concentration and turbidity were estimated for the depths of 0~1m, 0~2m and 0~transparency. The other data set of received SeaWiFS imagery for Lake Saroma and the ground truth chlorophyll a data observed by Saroma Fishery Cooperative Association in different stations (shown in Figure 1 (b)) for the same date of imagery were collected.

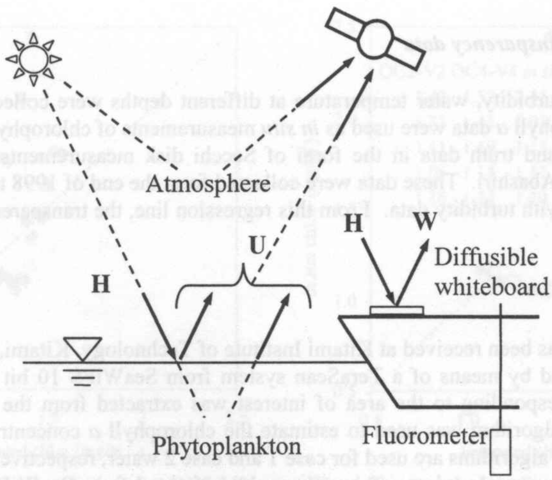


Fig. 2 Measurements of water surface reflectance and fluorometer data

Spectral radiation data collection

The spectral radiation data were collected over the period from 1997 to 2000; downward spectral irradiance (solar radiation, H in Figure 2) and upward water surface spectral radiance (U in Figure 2). The water surface reflectance data represent the ratio of reflected energy to incident energy with values ranging from 0 to 1. The upward water surface radiance is composed of two components: the direct reflected radiation at the water surface and the scattered radiation from transferred light under the water surface which possess water quality information. Solar radiation was measured by upward radiance from diffusible whiteboard.

Estimation of remote sensing reflectance from spectroradiometer

A spectroradiometer was used to measure upward radiance and downward irradiance. Through the components of light absorption and scattering coefficients, the water body controls the ratio between light scattering and absorption values, and thus determines the subsurface reflectance and in turn the emerged flux that will be sensed by radiometers (Jupp et al (3)). Because the medium composition affects the absorption and scattering coefficients differently at various wavelengths, the resulting spectral distribution can be mathematically modeled and/or measured by a spectroradiometer from above and under the water surface, and thus can be used to provide information about the water quality. As it is shown in Figure 2, solar radiation can be measured by determining the amount of H, while reflection constituents from water surface and under water surface can be measured by knowing the amount of U. But it is very difficult to measure solar radiation directly; therefore the upward radiation from the diffusible whiteboard is measured for solar radiation, which can be considered equal to solar radiation due to the reflectance 1 in all directions. In view of this, we measured reflected energy W from diffusible whiteboard by means of spectroradiometer for measuring solar energy. Reflectance R_r for any particular wavelength can be estimated by

$$R_r = \frac{\pi U}{H} \quad (1)$$

$$H = \pi W \quad (2)$$

Therefore, remote sensing reflectance can be calculated by

$$R_{rs} = \frac{U}{H \cos\theta_0} \quad (3)$$

where, θ_0 is solar zenith angle.

Fluorometer and Transparency data

Chlorophyll *a*, turbidity, water temperature at different depths were collected by using a fluorometer sensor. These chlorophyll *a* data were used as *in situ* measurements of chlorophyll *a* concentration.

Well timed ground truth data in the form of Secchi disk measurements were used to estimate the transparency of Lake Abashiri. These data were collected from the end of 1998 to 2000. These transparency data were correlated with turbidity data. From this regression line, the transparency for remaining data were estimated.

SeaWiFS imagery

SeaWiFS data has been received at Kitami Institute of Technology, Kitami, Hokkaido, Japan. The data set has been processed by means of a TeraScan system from SeaWiFS 10 bit data to level 1b. Only the required portion corresponding to the area of interest was extracted from the full scene. After that, the swcolor2 (OC2-V2) algorithm was used to estimate the chlorophyll *a* concentration. In TeraScan system, swcolor and swcolor2 algorithms are used for case 1 and case 2 water, respectively. Therefore, chlorophyll *a* concentration both for case 1 and case 2 water can be estimated from SeaWiFS data in our laboratory by using the facilities of TeraScan system.

METHODOLOGY

Chlorophyll a concentration estimated by SeaWiFS data

In TeraScan system OC2-V2 algorithm is used to estimate the chlorophyll *a* concentration for case 2 water. But NASA has published the new version, OC4-V4. The fundamental equations of OC2-V2 and OC4-V4 algorithms are as follows:

$$Chl.a = 10^{(a_0 + a_1 * R + a_2 * R^2 + a_3 * R^3)} + a_4 \tag{4}$$

$$R = Log\{R_{rs}(490) / R_{rs}(555)\}$$

$$a = [0.2974,\ -2.2429,\ 0.08358,\ -0.0077,\ -0.0929\ ]$$

$$Chl.a = 10^{(a_0 + a_1 * R + a_2 * R^2 + a_3 * R^3 + a_4 * R^4)} \tag{5}$$

$$R = Log\{\max[R_{rs}(443),\ R_{rs}(490),\ R_{rs}(510)] / R_{rs}(555)\}$$

$$a = [0.366,\ -3.067,\ 1.93,\ 0.649,\ -1.532\ ]$$

where, $R_{rs}(443)$, $R_{rs}(490)$, $R_{rs}(510)$ and $R_{rs}(555)$ are remote sensing reflectance for SeaWiFS band center 443, 490, 510, and 555nm with band width 20nm, respectively. And R is the logarithmic value of remote sensing reflectance ratio for two selective bands. We estimated chlorophyll *a* concentration for Lake Saroma by using acquired SeaWiFS image and compared the results with *in situ* data. *In situ* chlorophyll *a* concentrations were collected from five stations (shown in Figure 1(b)) for 6 June 2002 in Lake Saroma. Some pixels of remote sensing estimated chlorophyll *a* did not appear with *in situ* measured locations, therefore *in situ* measurements and remote sensing estimation were interpolated using linear interpolation technique to incorporate *in situ* data with remote sensing estimation. A comparison between *in situ* measurements and OC2-V2 estimation is shown in Figure 3. Figure 4 shows the scattered plots and tabular form comparisons among *in situ* measurements with estimated chlorophyll *a* by using OC2-V2 and OC4-V4 algorithms for five stations. The analyses are based on interpolated estimated remote sensing data with the interpolated *in situ* measurements surrounding the five stations. Due to the lack of *in situ* measurements and the small number of remote sensing measurement's pixels, spatial interpolation was performed. Interpolated results of chlorophyll *a* concentration may vary with actual measurements, but the trend of variations of chlorophyll *a* concentration can be understood from these results. The variation for OC2-V2 and OC4-V4 are almost the same and show lower values compared with *in situ* measurements, though OC4-V4 shows slightly higher estimating values than those of OC2-V2.

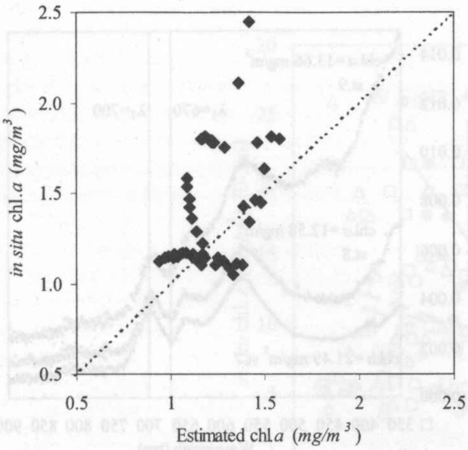


Fig. 3 Interpolated scattered plots for OC2-V2 estimated chlorophyll *a* concentration from SeaWiFS and *in situ* measurements in Lake Saroma, 6 June 2002

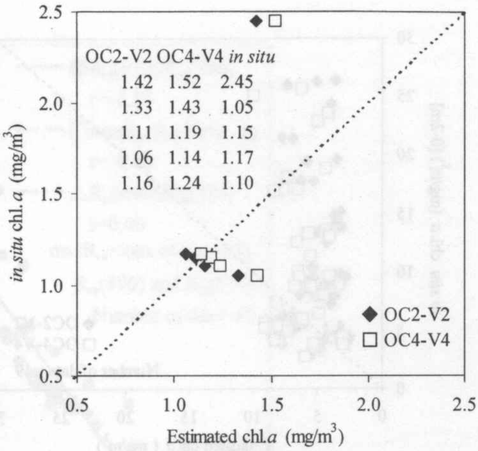


Fig. 4 Scattered plots for OC2-V2 and OC4-V4 estimated chlorophyll *a* concentration from SeaWiFS and *in situ* measurements in Lake Saroma, 6 June 2002

Assimilation of spectroradiometer data to compare with SeaWiFS data

Fluorometer and spectroradiometer data were collected for the year of 1997, 1998, 1999 and 2000 in the different stations of Lake Abashiri. The fluorometer data of chlorophyll *a* were considered as ground truth data. These data were accompanied by turbidity, salinity and water temperature data. In this study, only turbidity and chlorophyll *a* data were used. Spectroradiometer wavelength ranges from 350 to 900nm. Therefore, we prepared the spectral data corresponding to the wavelength of 443, 490, 510 and 555nm to assimilate with SeaWiFS data. Remote sensing reflectances can be estimated by using equation 3. However, the logarithmic value of remote sensing reflectance ratio *R* for two selective bands were estimated by

$$R = Log\left[\frac{R_{rs}(\lambda_1)}{R_{rs}(\lambda_2)}\right] = Log\left[\frac{\dfrac{U(\lambda_1)}{\pi W(\lambda_1)\cos\theta}}{\dfrac{U(\lambda_2)}{\pi W(\lambda_2)\cos\theta}}\right] = Log\left[\frac{U(\lambda_1)}{U(\lambda_2)}\frac{W(\lambda_2)}{W(\lambda_1)}\right] \quad (6)$$

Therefore, this equation becomes independent of solar zenith angle. By using Equations 4, 5 and 6, we estimated chlorophyll *a* for spectroradiometer reflectance which was assimilated according to SeaWiFS bands. Therefore, the measurements of chlorophyll *a* from spectroradiometer reflectance assimilate the chlorophyll *a* from SeaWiFS data. Comparisons among chlorophyll *a* estimated from spectral value of spectroradiometer and *in situ* chlorophyll *a* measured by fluorometer are shown in Figure 5. The ground truth data shows higher values compared with estimated results. Although OC4-V4 shows a little bit higher estimation compared with OC2-V2, it does not contribute significant development for case 2 water. Therefore, another estimation technique should be necessary to estimate the chlorophyll *a* concentration for highly turbid inland and coastal water.

The largest source of errors for chlorophyll *a* retrieval in case 2 waters are generally attributed to the bio-optical model that relates water leaving radiance or reflectance to the chlorophyll *a* concentration and to treatment of aerosol reflectance in the atmospheric correction procedure (Ruddick et al (8)). Latter one was only considered in OC2-V2 and OC4-V4 algorithms. Considering only blue to green, two-band ratios were used in these algorithms.

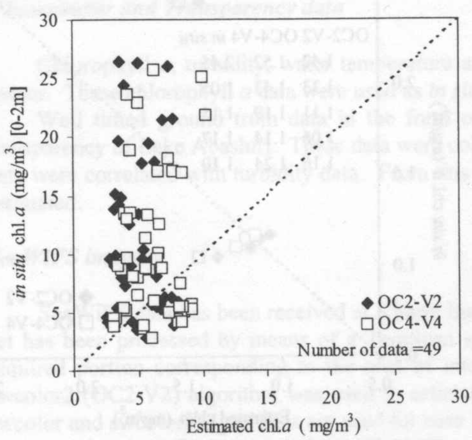


Fig. 5 Comparison among the assimilated chlorophyll *a* concentration with *in situ* data in Lake Abashiri, 1997-2000

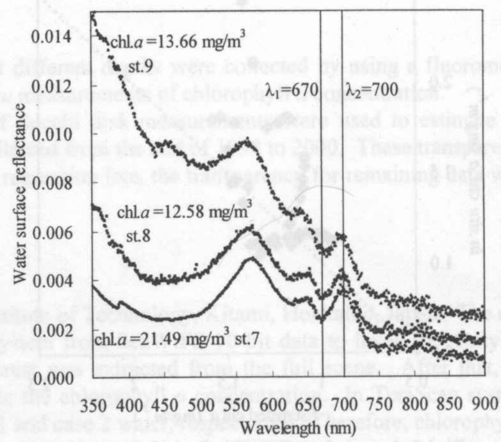


Fig. 6 Spectral reflectance measured at water surface for three known chlorophyll *a* concentrations averaged from 0 to 2m in Lake Abashiri, 21 August 1997

Selection of band wavelength for chlorophyll a concentration measurements

Many empirical models, with varying degrees of complexity, have been proposed in the past two decades to relate the backscattering properties observed in the concentration of dissolved substances in the water column. These models may use information in single or multiple bands, and employ different functional forms like the power function, multiple regression hyperbolic, second-order and third-order polynomials, or most commonly the log-transformation (Fireston and Hooker (2)). Normally, most of the algorithms were developed for case 1 water by using blue-green two-band ratio. Blue-green two-band ratio algorithms are popular for case 1 water, which may not be appropriate for case 2 water.

Both field and laboratory spectrometric measurements of reflectance and absorption are essential to develop the semi-empirical and analytical (radiative transfer) models that can describe the interactions of light and in-water materials (Dekker (1); Oki and Yasuoka (7)). In this study, field spectrometric measurements were used. Field spectra of both the materials of interest and other materials present in the environment can be used to address such issues as to what spatial and spectral resolutions are required for detection. Some field measured spectral reflectances at the water surface for the absorption of different chlorophyll *a* concentration in Lake Abashiri are shown in Figure 6.

Chlorophyll *a* is a phytopigment present in all algae groups in inland waters and shows absorption bands in the blue wavelength at 440nm and in the red wavelength at near 670nm (Figure 6), leaving a maximum green reflectance at 570nm due to an electron excitation process. But the band near 670nm shows a distinct absorption for this case. The red edge ascent near 700nm that is narrowed to a peak by growing water absorption in the near infrared is also correlated to increasing chlorophyll *a* contents.

A satellite-based sensor detects only the effects of the total absorption coefficients, where the absorption of phytoplankton 670-700nm is nearly equal to the absorption of total particulates (Ruddick et al (8)). Therefore, it is very difficult to retrieve chlorophyll *a* for case 2 water without using the bands ranges within 670-700nm. Normally, the band ratios algorithms used in phytoplankton retrieval have a good correlation for case 1 water (Tassan (10)). In view of this, we examined spectral bands ratio against the measured chlorophyll *a* that is shown in Figure 7. Bands ratio 670/700 shows a good correlation compared with other bands ratios which were used in OC2-V2 and OC4-V4 algorithms.

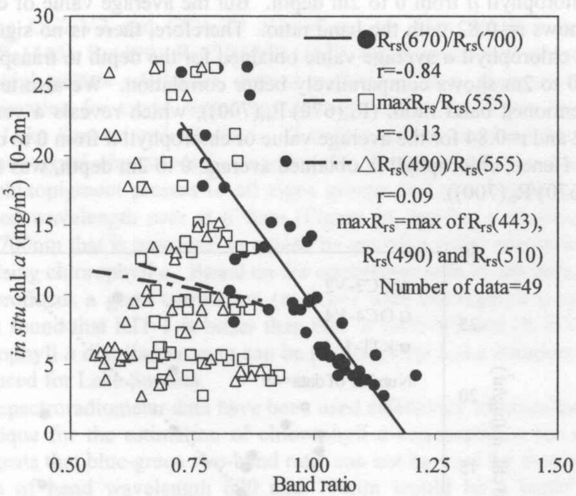
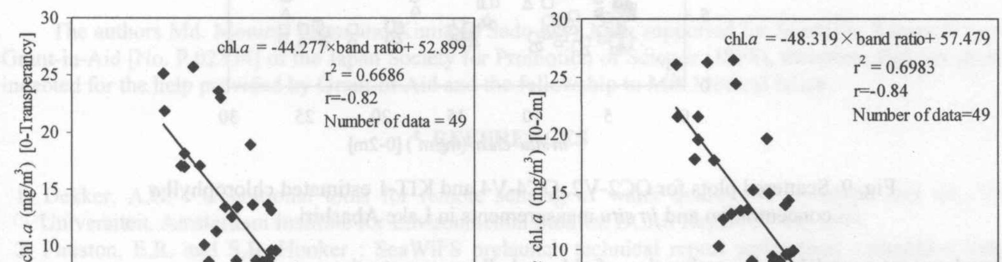


Fig. 7 Correlation of chlorophyll *a* concentration with different two-band ratio in Lake Abashiri, 1997-2000



(a) Chlorophyll a averaged from 0 to transparency

(b) Chlorophyll a averaged from 0 to 2 meter

Fig. 8 Correlation of observed averaged chlorophyll *a* with spectral band ratio ($R_{rs}(670)$/ $R_{rs}(700)$) in Lake Abashiri, 1997-2000

Influence of water depth on averaged chlorophyll a concentration

Based on the correlation with the *in situ* data, one of the most important relationships observed in this study was the relationship between spectral bands ratio and the average of chlorophyll *a* concentration from water surface to the depth up to the water transparency. Water transparency was measured by using Secchi disk depth. The average transparency of Lake Abashiri is 1.60m. The transparency (Secchi disk depth) is negatively correlated with turbidity, which shows correlation coefficient r=-0.64. The average of chlorophyll *a* concentration was calculated from 0 to 1m, 0 to the depth of water transparency and 0 to 2m depth. The correlation between the band ratio ($R_{rs}(670)/R_{rs}(700)$) and chlorophyll *a* concentration averaged in the depths mentioned above are shown in Figures 8(a) and 8(b). The average value for chlorophyll *a* from 0 to the depth of transparency shows r=-0.82 with the band ratio, while r=-0.84 is shown in Figure 8(b) for the averaged value of chlorophyll *a* from 0 to 2m depth. But the average value of chlorophyll *a* concentration from 0 to 1m also shows r=-0.82 with the band ratio. Therefore, there is no significant difference between the correlations with chlorophyll *a* average value obtained for the depth to transparency and 2m, though the average value from 0 to 2m shows comparatively better correlation. We also tested the correlation for the inverse of above mentioned band ratio, ($R_{rs}(670)/R_{rs}(700)$), which reveals a very similar correlation with positive value r=0.82 and r=0.84 for the average value of chlorophyll *a* from 0 to depth of transparency and 0 to 2m, respectively. Hence, chlorophyll *a*, obtained average 0 to 2m depth, was appeared to correlate better with band ratio ($R_{rs}(670)/R_{rs}(700)$).

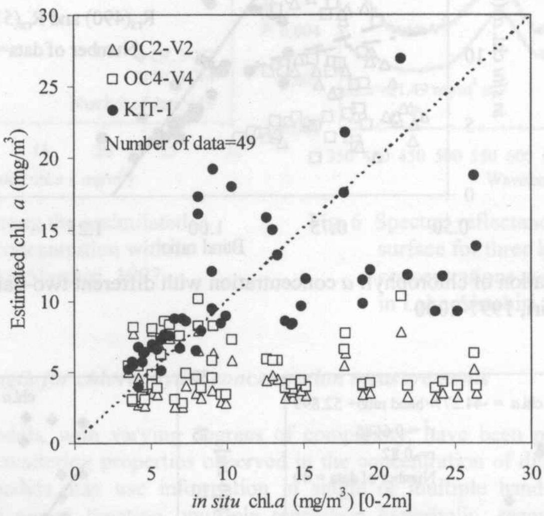


Fig. 9 Scattered plots for OC2-V2, OC4-V4 and KIT-1 estimated chlorophyll *a* concentration and *in situ* measurements in Lake Abashiri

Development a model for the estimation of chlorophyll a concentration

In the foregoing section, a liner correlation between the remote sensing reflectance ratio of band center 670 and 700nm with band width 20nm and the chlorophyll *a* concentration averaged from 0 to 2m was found. Therefore, to a make similar equation of OC2-V2 and OC4-V4, a new logarithmic relationship was developed by using the remote sensing reflectance ratio of 670 and 700nm with *in situ* chlorophyll *a* concentration averaged from 0 to 2m for Lake Abashiri. This relationship can be expressed as follows:

$$Chl.a = 10^{(a_0 + a_1 * R)} \quad (7)$$

$$R = Log\{R_{rs}(670)/R_{rs}(700)\}$$

$$a = [0.9092, \ -3.820], \quad correlation\ coefficient\ \ r = 0.70$$

Hereafter, this relation is called as KIT-1 equation. A comparison of scattered plots among the *in situ* chlorophyll *a* concentration with the estimated chlophyll *a* concentration using OC2-V2, OC4-V4 and KIT-1 equations are shown in Figure 9. In contrast, KIT-1 shows the estimated values towards the diagonal line, which means that the estimated results appear close to *in situ* measurements, while OC2-V2 and OC4-V4 shows the lower estimated chlorophyll *a*. The KIT-1 shows substantial improvement to estimate chlorophyll *a* for case 2 water compared with OC2-V2 and OC4-V4. Therefore, the KIT-1 equation seems to be a more suitable algorithm for estimating of chlorophyll *a* concentration from May to October except of spring and summer blooming.

RESULTS AND DISCUSSIONS

Sigmoid form of the OC2-V2 and OC4-V4 algorithms are very sensitive to small variations of $R_{rs}(490)/R_{rs}(555)$ or $\max[R_{rs}(443), R_{rs}(490), R_{rs}(510)]/R_{rs}(555)$, and then estimate unrealistically high or low chlorophyll *a* in cases of high yellow substances, detrital and/or accessory pigment absorption. These two algorithms show high estimation for lower ranges and low estimation for higher ranges of chlorophyll *a* concentrations in case of Lake Saroma and Abashiri. Therefore, it was revealed that blue-green two-band ratio algorithm does not show good adaptations for case 2 water, though which is popular for case 1 water.

Chlorophyll *a* is a phytopigment present in all algae groups in Lake Abashiri, which shows distinct absorption bands in the red wavelength near at 670nm (Figure 6), leaving a maximum green reflectance. The red edge ascent near 700nm that is narrowed to a peak by growing water absorption in the near infrared is also correlated to increasing chlorophyll *a*. Based on the correlation with *in situ* data, the ratio of band 670 and 700nm wavelength produces a good correlation (r=-0.84) with chlorophyll *a* concentration averaged from 0 to 2m depth. It is found that KIT-1 is better than that of OC2-V2 and OC4-V4, therefore by using this KIT-1 model, a chlorophyll *a* distribution map can be produced for Lake Abashiri and similarly another KIT-1 model can be produced for Lake Saroma.

Therefore, hand-held spectroradiometer data have been used effectively to assimilate the spectral band to the remote sensing technique for the estimation of chlorophyll *a* concentration for case 2 water in Lake Abashiri. This study suggests that blue-green two-band ratio can not be used for monitoring chlorophyll *a* in case 2 water. The ratio of band wavelength 670 and 700nm would be a better way to monitor the chlorophyll *a* concentration for inland and high turbid water.

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APPENDIX – NOTATION

The following symbols are used in this paper:

a	=	coefficients for different order of exponential equations (a_1, a_2, a_3, a_4, etc.);
H	=	solar spectral irradiance to water surface ($\mu w\ cm^{-2}\ nm^{-1}$);
r	=	correlation coefficient;
R	=	logarithmic value of remote sensing reflectance ratio for two selective bands;
R_r	=	water surface reflectance;
R_{rs}	=	remote sensing reflectance (sr^{-1});
U	=	upward water surface spectral radiance ($\mu w\ cm^{-2}\ sr^{-1}\ nm^{-1}$);
W	=	reflected radiance of H on diffusible whiteboard ($\mu w\ cm^{-2}\ sr^{-1}\ nm^{-1}$);
λ	=	selected wavelength (nm); and
θ_0	=	solar zenith angle (rad).

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