AN ESTIMATION METHOD OF APPROPRIATE CHLOROPHYLL-A CONCENTRATIONS VIA THE LINEAR COMBINATION INDEX FOR SENTINEL-2/MSI DATA IN HIROSHIMA BAY

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ABSTRACT: Although many methods by band ratio have been reported in the estimation of the Chl.a concentration by satellite, the chlorophyll-a concentration estimation via the linear combination index (LCI) proposed by Frouin et al. (2006) can mitigate the influence of atmosphere to some extent. When the computing for the LCI, we usually use 3 to 4 bands from visible to near infrared, but there are few discussions of the combination. Therefore, we report the appropriate band combination in estimating the Chl.a concentration via the LCI for Sentinel-2A/MSI data. In the analysis, the relationship between the LCI in Hiroshima Bay calculated from Sentinel-2A/MSI data and the Chl.a concentration based on the water quality survey results was approximated by exponential function. As a result of the analysis, it was clarified that the following: First, for the case of three-band combinations, (1) band combinations of 1, 2 and 3, (2) band combinations of 1, 4 and 8, (3) band combinations of 2, 3 and 8, and (4) band combinations of 2, 4 and 8 indicated the coefficients of determination R^2 greater than 0.5. Here, the R^2 of band combinations of 1, 2 and 3 was the higher with 0.524. Secondly, for the case of four-band combinations, (1) band combinations of 1, 2, 3 and 4, (2) band combinations of 1, 2, 3 and 8, (3) and band combinations of 1, 2, 4 and 8 indicated the coefficients of determination R^2 greater than 0.5. Here, the R^2 of band combinations of 1, 2, 3 and 8 was the highest with 0.637. Thirdly, in these two band combinations, the Chl.a concentration as increased with the LCI increase.

1. INTRODUCTION

Oyster farming is thriving in Hiroshima Prefecture, and the account for about 63% of Japan's production. Hiroshima oysters are farmed and produced mainly in the northern part of Hiroshima Bay. The nutrients such as chlorophyll-a (Chl.a) concentrations are very important marine information in oyster farming. There are various methods for the Chl.a analysis using satellite data. The atmospheric influence can mitigate to some extent in an estimating method of the Chl.a concentration via the linear combination index (LCI) proposed by Frouin et al. (2006). The estimating methods of the Chl.a concentration via LCI have been reported in several papers (Sakuno, 2013, Oguro, 2021,). When the computing for the LCI, we usually use three to four bands from visible to near infrared, but there are few discussions of the combination. This paper deals with the finding an appropriate band combination for estimating the Chl.a concentration via the LCI for Sentinel-2A/MSI data.

2. DATA

As a satellite data, a total of four Sentinel-2A/MSI data observed over Hiroshima Bay (Entity ID: T53SKT, T53SKU) on September 11th, September 14th, November 10th, and November 13th, in 2019 were used to compute the LCI. On the other hand, as a reference value of the Chl.a concentration (at depth 0 m), a total of three water quality survey results measured at 21 locations in Hiroshima Bay by the 6th Regional Coast Guard Headquarters (2021) on September 3, November 5, and November 7 in 2019 were used.

3. METHOD

The LCI proposed by Frouin (2006) is defined as the sum of the 3 or 4 bands of the aerosol reflectance $Ra(\lambda_i)$ and the water reflectance $Rw\ (\lambda_i)$ as follows:

$$\mathrm{LCI} = \sum_{i=1}^{k} a_i R_a\,(\lambda_i) + \sum_{i=1}^{k} a_i\, R_w(\lambda_i)\,, \tag{1}$$

where to eliminate most of the atmospheric influence on the LCI, we approximate the aerosol reflectance $Ra(\lambda_i)$ as a function of wavelength λ_i and set the sum of $a_i*Ra(\lambda_i)$ to zero.
That is, the sum of $a_i*Ra(\lambda_i)$ on the first term of Eq. (1) replaces as follows:

$$\sum_{i=1}^{k} a_i R_a(\lambda_i) \approx \sum_{i=1}^{k} a_i \lambda_i^{\eta_j} = 0. \tag{2}$$

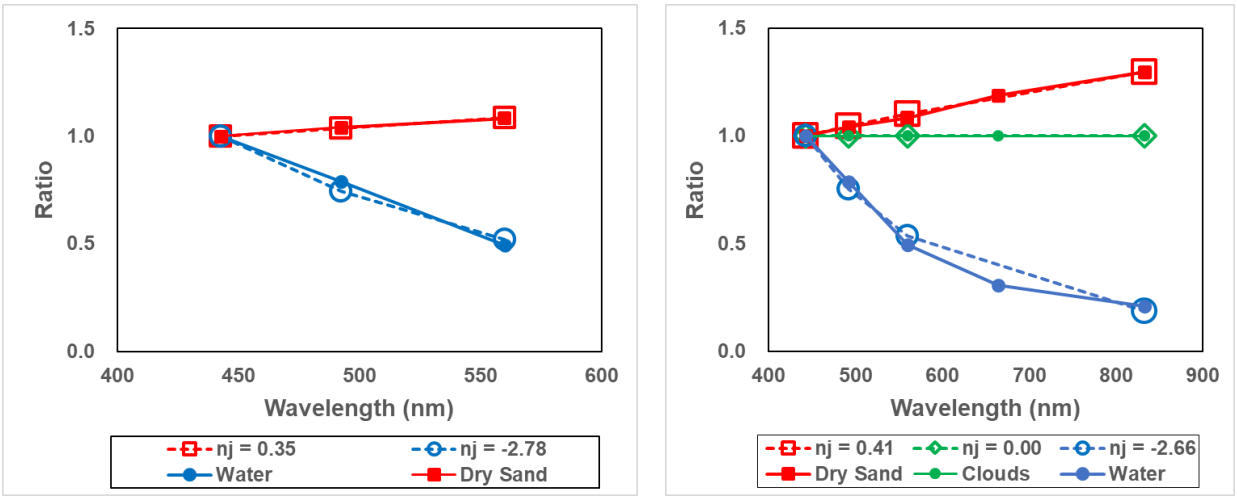
Consequently, the LCI of Eq. (1) is rewritten as follows:

$$\mathrm{LCI} \approx \sum_{i=1}^{k} a_i R_w(\lambda_i). \tag{3}$$

In additions Eq. (2) and Eq. (3) were solved by the following procedure.

Firstly, the wavelength λ_i are assumed the following Sentinel-2A bands: (1) band 1 (442.7 nm) which is the absorption band of chlorophyll a, (2) band 2 (492.4 nm) which is the absorption band of chlorophyll b, (3) band 3 (559.8 nm) which is a non-absorption band of chlorophyll a and b, (4) band 4 (664.6 nm) which is a non-absorption band of chlorophyll a and b, and (5) band 8 (832.8 nm) which is the indicating aerosol effect. From these five bands, we selected three- or four- band combinations (k=3-4) that includes either band 1 or band 2, or both.

Secondly, we approximated the exponent η_j with the normalized reflectance characteristics of dry sand and water observed in our laboratory. For example, Figure 1(a) shows the case of the band combination of 1, 2 and 3, and Figure 1(b) shows the case of band combination of 1, 2, 3 and 8.



(a) The case of band combinations of 1, 2 and 3. (b) The case of band combinations 1, 2, 3 and 8

Figure 1. Normalized reflectance characteristics of dry sand and water.

Thirdly, for the easier calculation the coefficient a_1 of the shortest band of wavelength was fixed to 1, and the remaining coefficients from a_2 to a_3 for three-band combinations, or those from a_2 to a_4 for four-band combinations were solved by the simultaneous linear equation. For example, Eq. (4) shows the case of the band combinations of 1, 2 and 3 for $\eta_1=0.35$ and $\eta_2=-2.78$, and Eq. (5) shows the case of band combinations of 1, 2, 3 and 8 for $\eta_1=0.41$, $\eta_2=0.00$ and $\eta_3=-2.66$.

$$\begin{cases} \lambda_1^{0.35} + a_2\lambda_2^{0.35} + a_3\lambda_3^{0.35} = 0, \\ \lambda_1^{-2.78} + a_2\lambda_2^{-2.78} + a_3\lambda_3^{-2.78} = 0. \end{cases} \tag{4}$$

$$\begin{cases} \lambda_1^{0.41} + a_2\lambda_2^{0.41} + a_3\lambda_3^{0.41} + a_8\lambda_8^{0.41} = 0, \\ \lambda_1^{0.00} + a_2\lambda_2^{0.00} + a_3\lambda_3^{0.00} + a_8\lambda_8^{0.00} = 0, \\ \lambda_1^{-2.66} + a_2\lambda_2^{-2.66} + a_3\lambda_3^{-2.66} + a_8\lambda_8^{-2.66} = 0. \end{cases} \tag{5}$$

Finally, the LCI of Eq. (3) was solved. For example, Eq. (6) shows the case of the band combinations of 1, 2 and 3, and Eq. (7) shows the case of band combinations of 1, 2, 3 and 8.

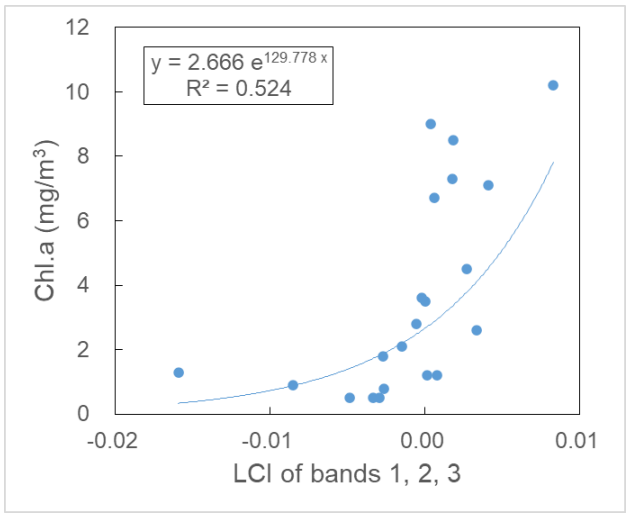
$$LCI \approx R_w(\lambda_1) - 2.1147R_w(\lambda_2) + 1.1007R_w(\lambda_3). \quad (6)$$

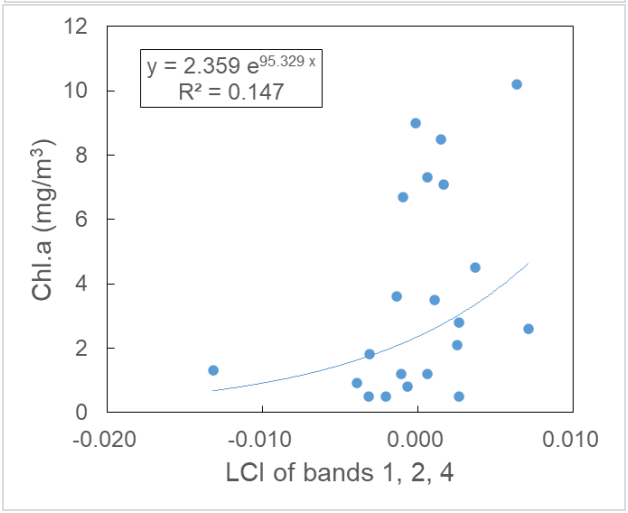
$$LCI \approx R_w(\lambda_1) - 2.4276R_w(\lambda_2) + 1.6122R_w(\lambda_3) - 0.1846R_w(\lambda_8). \quad (7)$$

4. RESULTS

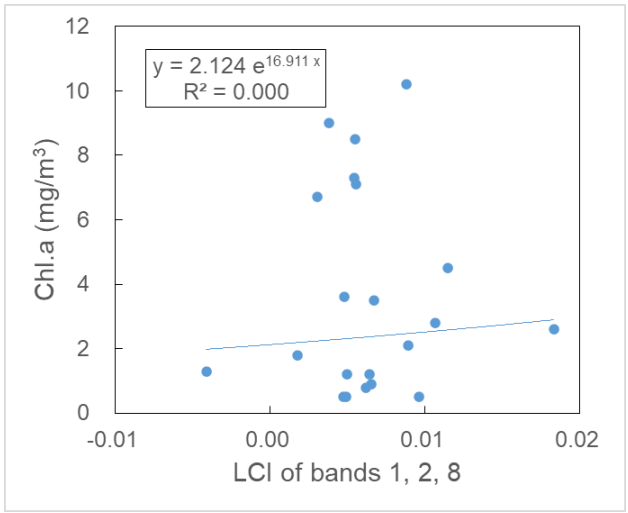
4.1 Results of various three-band combinations

First, as the three-band combinations (k=3) that include either band 1 or band 2, or both, we assumed the follows nine cases: (1) band combinations of 1, 2 and 3, (2) band combinations of 1, 2 and 4, (3) band combinations of 1, 2 and 8, (4) band combinations of 1, 3 and 4, (5) band combinations of 1, 3 and 8, (6) band combinations of 1, 4 and 8, (7) band combinations of 2, 3 and 4, (8) band combinations of 2, 3 and 8, and (9) band combinations of 2, 4 and 8.
Next, the relationship between the LCI in Hiroshima Bay calculated from Sentinel-2A/MSI data and the Chl.a based on the water quality survey results of the 6th Regional Coast Guard Headquarters was approximated by exponential function. Here, these relationship between the LCI and the measured Chl.a were shown in Figure 1.

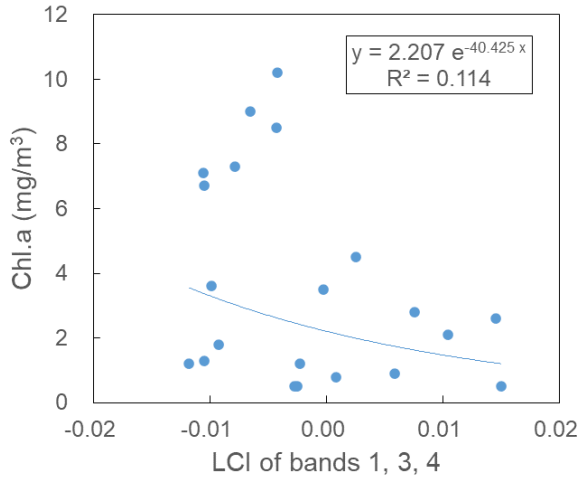




(a) Band combinations of 1, 2 and 3 (b) Band combinations of 1, 2 and 4

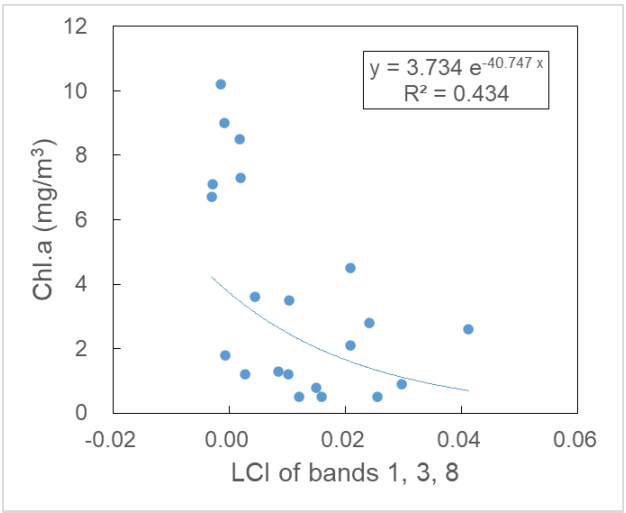


(c) Band combinations of 1, 2 and 8

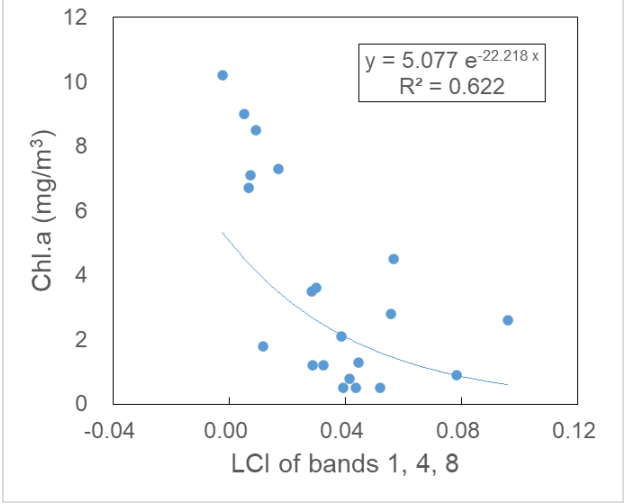


(d) Band combinations of 1, 3 and 4

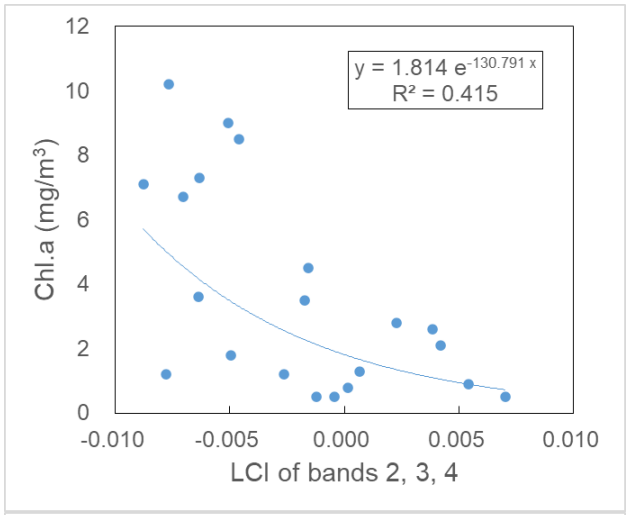
Figure 1. Relation between the LCI and the measured Chl.a for three-band combinations.



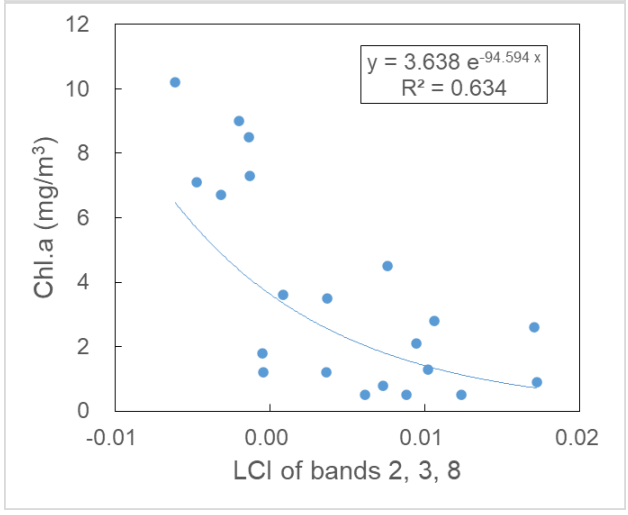
(e) Band combinations of 1, 3 and 8



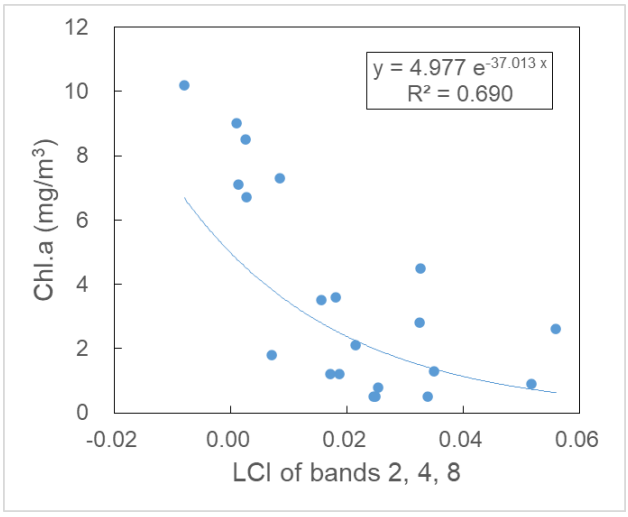
(f) Band combinations of 1, 4 and 8



(g) Band combinations of 2, 3 and 4



(h) Band combinations of 2, 3 and 8



(i) Band combinations of 2, 4 and 8

Figure 1. Relation between the LCI and the measured Chl.a for three-band combinations (continued).

Table 1. The exponents η_j and the coefficients of determination R^2 for three-band combinations (k=3)

Band combinations	η_1	η_2	R^2

1, 2, 3	0.35	-2.78	0.524
1, 2, 4	0.42	-2.73	0.147
1, 2, 8	0.41	-2.42	0.000
1, 3, 4	0.41	-2.96	0.114
1, 3, 8	0.41	-2.76	0.434
1, 4, 8	0.42	-2.72	0.622
2, 3, 4	0.42	-3.32	0.415
2, 3, 8	0.42	-2.91	0.634
2, 4, 8	0.42	-2.84	0.690

Finally, the exponents ηj and the coefficients of determination for the three-band combinations were shown in Table 1. From Table 1, the coefficients of determination R^2 greater than 0.5 out of the three-band combinations were the following four cases: (1) band combinations of 1, 2 and 3, (2) band combinations of 1, 4 and 8, (3) band combinations of 2, 3 and 8, and (4) band combinations of 2, 4 and 8. Here, the R^2 value was the highest with 0.690 in the band combinations of 2, 4 and 8, although in this band combinations, the Chl.a concentration as decreased with the LCI increase. So, we selected the band combinations of 1, 2 and 3 which the Chl.a concentration as increased with the LCI increase although the R^2 value was 0.524. The Chl.a estimation formula for this band combinations is shown in Eq. (8).

$$Chl.a \approx 2.6661 \exp(129.7780\, LCI). \tag{8}$$

As an example, the estimated Chl.a concentration image for bands 1, 2 and 3 on November 13th, 2019 was shown in Figure 2.

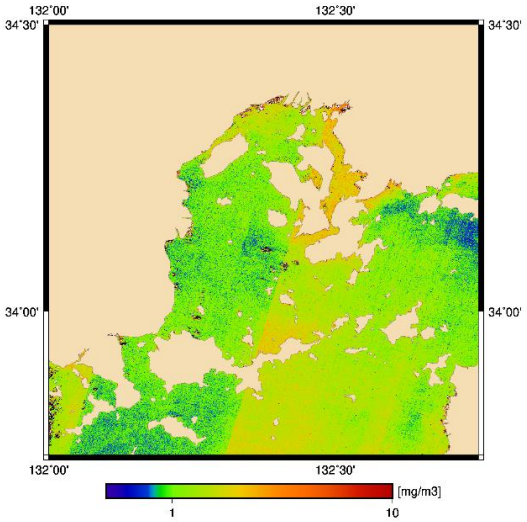
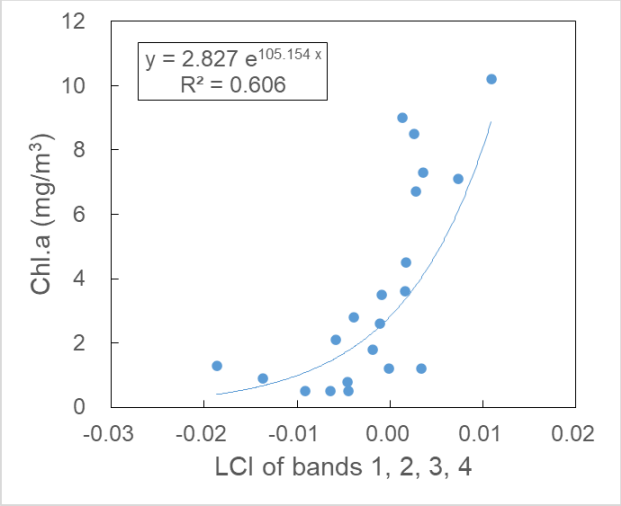


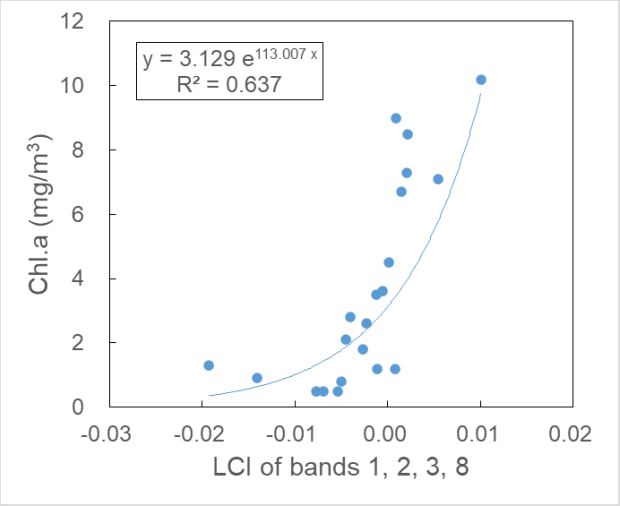
Figure 2. Example of the estimated Chl.a concentration image for bands 1, 2 and 3 on November 13th, 2019.

4.2 Results of various four-band combinations

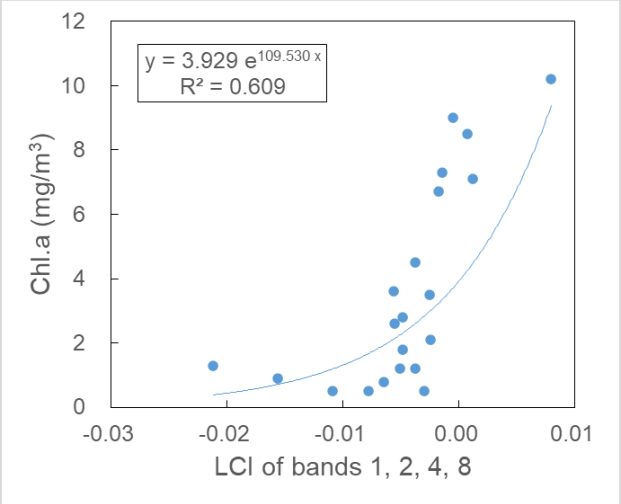
First, as the four-band combinations (k=4) that include either band 1 or band 2, or both, we assumed the follows five cases: (1) band conventions of 1, 2, 3 and 4, (2) band conventions of 1, 2, 3 and 8, (3) band conventions of 1, 2, 4 and 8, (4) band conventions of 1, 3, 4 and 8, and (5) band conventions of 2, 3, 4 and 8.
Next, the relationship between the LCI in Hiroshima Bay calculated from SWentinal-2A/MSI data and the Chl.a based on the water quality survey results of the 6th Regional Coast Guard Headquarters was approximated by exponential function. Here, these relationship between the LCI and the measured Chl.a were shown in Figure 3.



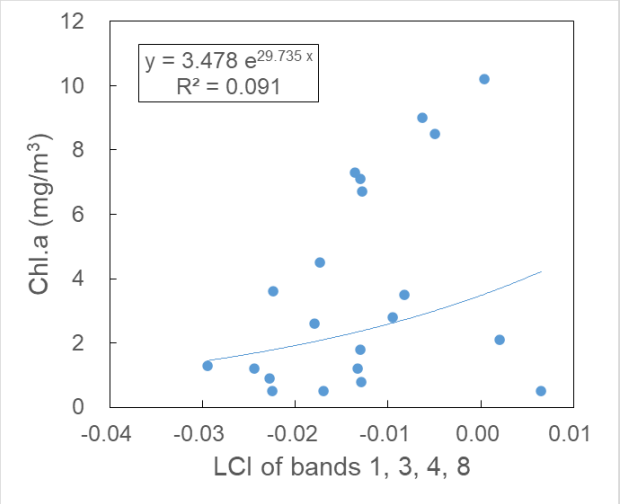
(a) Band combinations of 1, 2, 3 and 4



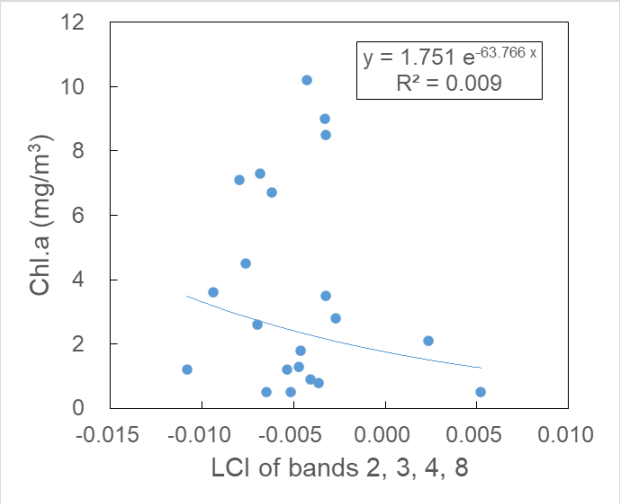
(b) Band combinations of 1, 2, 3 and 8



(c) Band combinations of 1, 2, 4 and 8



(d) Band combinations of 1, 3, 4 and 8



(e) Band combinations of 2, 3, 4 and 8

Figure 3. Relation between the LCI and the measured Chl.a for four-band combinations.

Table 2. The exponents η_j and the coefficients of determination R^2 for four-band combinations (k=4)

Band conventions	η_1	η_2	η_3	R^2
1, 2, 3, 4	0.41	0.00	-2.83	0.606
1, 2, 3, 8	0.41	0.00	-2.66	0.637
1, 2, 4, 8	0.42	0.00	-2.64	0.609
1, 3, 4, 8	0.41	0.00	-2.82	0.091
2, 3, 4, 8	0.42	0.00	-3.02	0.009

Finally, the exponent ηj and the coefficients of determination R^2 for the four-band combinations were shown in Table 2. From Table 2, the coefficients of determination R^2 greater than 0.5 out of the four-band combinations were the following three cases: (1) band conventions of 1, 2, 3 and 4, (2) band conventions of 1, 2, 3 and 8, and (3) band conventions of 1, 2, 4 and 8. Here, the R^2 value was the highest with 0.637 in the band combinations of 1, 2, 3 and 8. The Chl.a estimation formula for this band combinations is shown in Eq. (9).

$$Chl.a \approx 3.1287\ exp(113.0073\ LCI). \tag{9}$$

As an example, the estimated Chl.a concentration image for bands 1, 2, 3 and 8 on November 13th, 2019 was shown in Figure 4. Here, the estimated Chl.a concentrations indicated the almost same features of the band combinations 1, 2, and 3 in Figure 2.

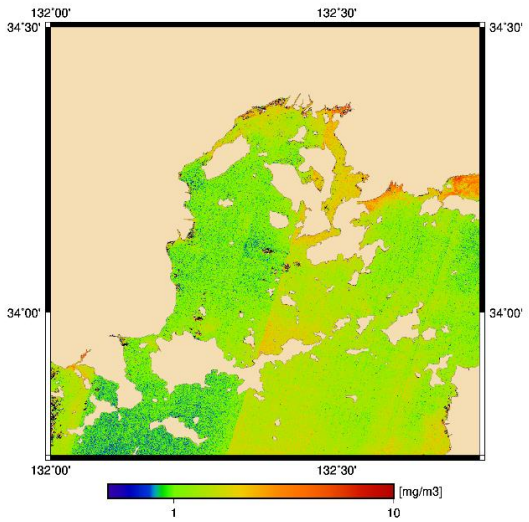


Figure 4. Example of the estimated Chl.a concentration image for bands 1, 2, 3 and 8 on November 13th, 2019.

5. CONCLUSIONS

In this paper, we investigated the appropriate band combination for estimating the Chl.a concentration via the LCI for Sentinal-2A/MSI data. As the relationship between the LCI in Hiroshima Bay calculated from Sentinel-2A/MSI data and the Chl.a concentration based on the water quality survey results was approximated, it was clarified that the following:

For the case of three-band combinations, (1) band combinations of 1, 2 and 3, (2) band combinations of 1, 4 and 8, (3) band combinations of 2, 3 and 8, and (4) band combinations of 2, 4 and 8 indicated the coefficients of determination greater than 0.5. Moreover, the coefficient of determination R^2 of band combinations of 1, 2 and 3 was the higher with 0.524. In this band combinations, the Chl.a concentration as increased with the LCI increase.

For the case of four-band combinations, (1) band combinations of 1, 2, 3 and 4, (2) band combinations of 1, 2, 3 and 8, and (3) band combinations of 1, 2, 4 and 8 indicated the coefficients of determination greater than 0.5. Moreover, the coefficient of determination R^2 of band combinations of 1, 2, 3 and 8 was the highest with 0.637. In this band combinations, the Chl.a concentration as increased with the LCI increase.

Here, the measurement of Chl.a concentration referenced in this analysis was not a fully simultaneous observation with satellite. Consequently, it is necessary to observe the measurement of Chl.a concentration simultaneously with a satellite observation and verify the results of this analysis.

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