Carbon, nitrogen, and chlorophyll *a* content of green *Noctiluca scintillans* in the Upper Gulf of Thailand

Masatoshi Nakakuni[1,*], Kazuhiko Ichimi[1,2], Thaithaworn Lirdwitayaprasit[3], Shettapong Meksumpun[4], Kuninao Tada[1,2]

Abstract

Noctiluca scintillans, which is common in coastal waters, significantly affects coastal biomass through bloom formation. This study has measured the cellular carbon, nitrogen, and chlorophyll *a* (Chl-*a*) content of natural green *Noctiluca* from the western Upper Gulf of Thailand. The carbon content ranged from 195–556 ng-C cell^{-1} (mean: 241 ± 132 ng-C cell^{-1}), while nitrogen content varied between 17–55 ng-N cell^{-1} (mean: 36 ± 6 ng-N cell^{-1}). Chl-*a* content averaged 9.80 ± 0.78 ng cell^{-1}. Notably, green *Noctiluca* exhibited higher carbon content than red *Noctiluca* of identical cell size, potentially because of their endosymbionts.

Keywords

Noctiluca scintillans; Chlorophyll *a*; Carbon biomass; Southeast Asia

[1] *Seto Inland Sea Regional Research Center, Kagawa University, Kagawa 761–0130, Japan*
[2] *Department of Applied Biological Sciences, Faculty of Agriculture, Kagawa University, Miki, Kagawa 761–0795, Japan*
[3] *Department of Marine Science, Chulalongkorn University, Phyathai Rd., Bangkok 10330, Thailand*
[4] *Department of Marine Science, Faculty of Fisheries, Kasetsart University, Bangkok 10900, Thailand*
*****Correspondence**: masatoshi.nakakuni@gmail.com (M. Nakakuni)

1. Introduction

Noctiluca scintillans (Macartney), a heterotrophic dinoflagellate, is found in coastal areas globally (Harrison et al., 2011). Its ecological characteristics vary drastically between red and green colors. Red *Noctiluca* relies entirely on other organisms for food (Nakamura, 1998). In contrast, green *Noctiluca* harbors a photosynthetic endosymbiont, *Protoeuglena noctilucae* (formerly *Pedinomonas noctilucae*), which shares the products of photosynthesis (Sweeney, 1976; Wang et al., 2016; Furuya et al., 2006; Saito et al., 2006). The presence of this endosymbiont in green *Noctiluca* depends on the water temperature that is favorable for its survival (Furuya et al., 2023). Additionally, studies in various marine ecosystems have demonstrated how environmental factors such as temperature, salinity, and nutrient dynamics influence the distribution and abundance of *Noctiluca* (either red or green) and other planktonic organisms, providing insights into the complex interactions between marine food webs and environmental conditions (Ara et al., 2013; Bisinicu et al., 2023a, 2023b, 2024; Kitatsuji et al., 2019; Miyaguchi et al., 2006; Watanabe et al., 2024).

Previous studies have examined various aspects of the relationship between green *Noctiluca* and its symbiotic algae, as well as their ecological dynamics. Specifically, green *Noctiluca* utilizes symbiotic algae as a carbon source, but it cannot survive for more than two weeks without prey, thus suggesting that symbiotic algae cannot serve as a complete nutritional source (Sweeney, 1971; Hansen et al., 2004). On the contrary, Furuya et al. (2006) isolated strains that survived across generations without a food supply, suggesting that green *Noctiluca* could grow photoautotrophically. Saito et al. (2006) provided experimental evidence for this hypothesis using quantitative photosynthesis and respiration measurement data, experimentally supporting facultative phagotrophy. Furthermore, Gomes et al. (2018) confirmed in their study that in cultures without prey, cells survived and divided for more than 3 months, with net photosynthetic rates reaching up to 3.2 nmol O_2 cell^{-1} h^{-1} and respiration rates of 0.8 nmol O_2 cell^{-1} h^{-1}, sufficient levels to support growth. Recent studies have shown that green *Noctiluca* is maintained through a positive feedback mechanism where nutrients obtained through predation are released as ammonium, which stimulates phytoplankton that are subsequently preyed upon and combined with active sexual reproduction involving mass gametes (Luo et al., 2022). Collectively, these studies revealed that green
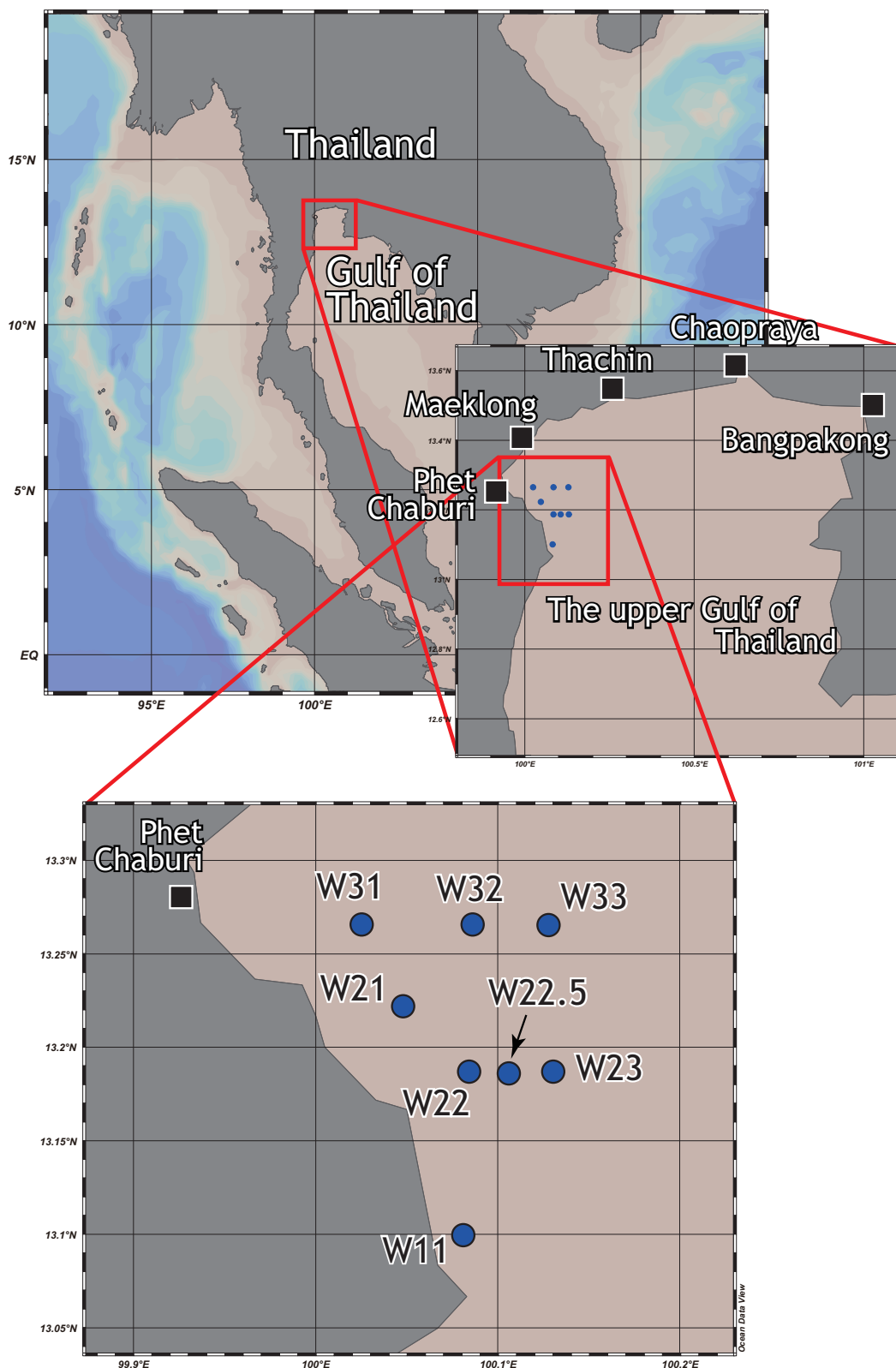
Figure 1. Map of sampling sites. 2008 surveys were conducted in W11, W21–23, and W31–33; 2010 surveys were conducted in W22, W22.5, W23, and W31–33. The square symbol indicates the location of the river mouths.

Noctiluca has evolved a flexible nutritional strategy that integrates photosynthesis, predation, and nutrient recycling.

Noctiluca often triggers severe blooms, causing significant harm to fishing and tourism industries (do Rosário Gomes et al., 2014; Hallegraeff et al., 2019). In the Upper Gulf of Thailand (UGoT), outbreaks of green *Noctiluca* are common along the coast during the non-monsoon months (February–April) and extend into the central UGoT during the southwest monsoon (May–September) (Luang-on et al., 2023). The coastal areas of the UGoT are also experiencing intense eutrophication and hypoxia (Morimoto et al., 2021; Buranapratheprat et al., 2021). It is believed that green *Noctiluca* contribute to these conditions by releasing large amounts of organic matter during blooms (Morimoto et al., 2021).

Determining the cellular contents of carbon, nitrogen, and chlorophyll *a* (Chl-*a*) in *Noctiluca* is crucial for understanding biogeochemical cycles and the ecological structures within marine ecosystems. For example, Tada et al. (2000) estimated the cellular carbon and nitrogen content of red *Noctiluca*, contributing to improved carbon biomass estimates and enhancing our understanding of the impact of *Noctiluca* on ecosystems and its role in material cycling (Arashkevich et al., 2014; Karnan et al., 2017). Although Saito et al. (2006) reported the Chl-*a* content in green *Noctiluca*, their research focused on cultured cells rather than on natural populations. In this study, we determined the cellular contents of carbon, nitrogen, and Chl-*a* in natural green *Noctiluca* using field observations and presented new datasets. This study provides fundamental data for evaluating the contribution of green *Noctiluca* to marine biogeochemical cycles and ecosystem dynamics in coastal environments experiencing environmental change.

2. Material and methods

Samples were collected in November 2008 (W11, W21–23, and W31–33) and November 2010 (W22, W22.5, W23, and W31–33) from the western side of the UGoT by using a small boat (Figure 1). Surface water samples were obtained with buckets at these locations. During both sampling periods, the Chl-*a* levels and the number of green *Noctiluca* cells in the surface waters were measured (Holm-Hansen et al., 1965). For chlorophyll *a* analysis, 1 L of seawater was filtered through a 47-mm glass fiber filter (GF/F, Whatman), treated with a 9:1 acetone-water mixture, refrigerated overnight, and analyzed using a 10-AU fluorometer (Turner Designs, USA).

The green *Noctiluca* cell density was determined by filtering a known volume of surface seawater through a 150 μm mesh to concentrate the cells. The retained cells were then counted under a microscope. In 2008, at site W31, the dimensions of 10 cells were measured using a microscope, and the Chl-*a* content was determined from approximately 200 cells collected on a GF/F filter ($n = 3$). Additionally, approximately 400 cells were collected on a

Table 1. Chlorophyll-*a* content and green *Noctiluca scintillans* status obtained at each site.

Year	Site	Total Chl-*a* [μg L^{-1}]	Green *Noctiluca* [cells L^{-1}]	Green *Noctiluca* cellular Chl-*a*[*] [ng cell^{-1}]	Contribution of green *Noctiluca* Chl-*a*[**] [%]	Green *Noctiluca* cellular carbon[***] [ng-C cell^{-1}]	Green *Noctiluca* cellular nitrogen[***] [ng-N cell^{-1}]	C:N[***] [mol mol^{-1}]
2008	W11	14.8	661	6.5	44	–	–	–
	W21	10.7	896	8.8	82	–	–	–
	W22	5.3	230	2.3	42	–	–	–
	W23	–	273	2.7	–	–	–	–
	W31	19.4	1033	10.1	52	556(96)[4]	41(12)[4]	16.7(3.7)[4]
	W32	6.2	230	2.3	36	–	–	–
	W33	11.4	867	8.5	75	–	–	–
2010	W22	10.7	1355	–	–	506(350)[3]	55(11)[3]	10.5(0.8)[3]
	W22.5	15.4	667	–	–	278(52)[3]	32(11)[3]	11.1(2.6)[3]
	W23	7.0	288	–	–	326(–)[2]	18(–)[2]	20.3(–)[2]
	W31	5.3	1222	–	–	217(18)[3]	17(5)[3]	16.4(5.0)[3]
	W32	4.3	1488	–	–	195(38)[5]	19(6)[5]	12.3(2.4)[5]
	W33	2.9	1577	–	–	195(21)[3]	20(4)[3]	11.8(3.3)[3]

[*] Calculated by multiplying the mean cellular Chl-*a* content of green *Noctiluca* (9.8 ng cell^{-1}) obtained at Site W31 in 2008 by the number of green *Noctiluca* (cells L^{-1}) at each site.
[**] Calculated as green *Noctiluca* Chl-*a* content relative to total Chl-*a* content.
[***] The numbers in parentheses indicate the standard deviation. Superscript numbers outside parentheses indicate the number of samples.
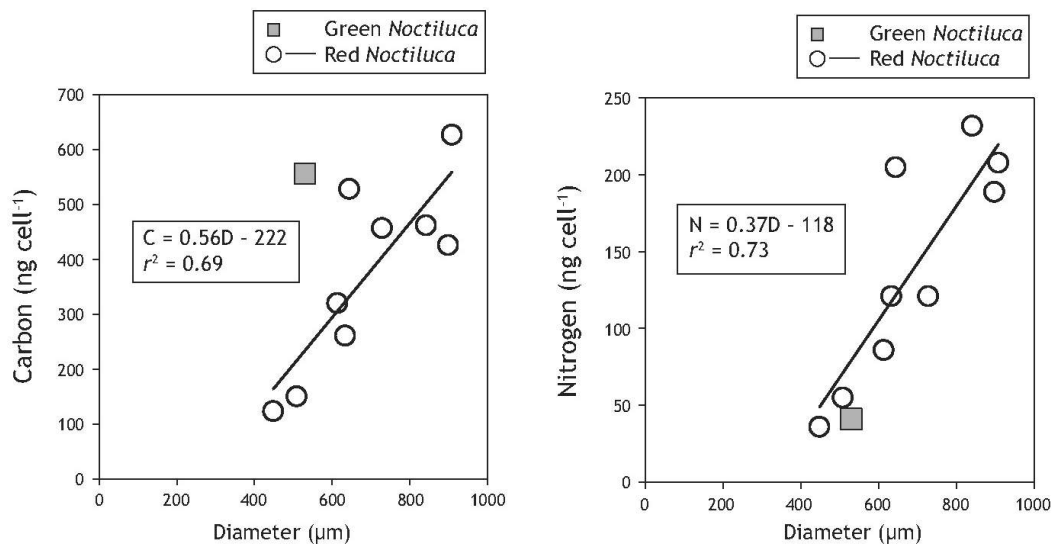
Figure 2. Relationship between cellular carbon content (left) and nitrogen content (right) versus cell diameter of green *Noctiluca*. Gray squares represent data from green *Noctiluca* collected at station W31 in 2008, while white circles show data from red *Noctiluca* cited from Tada et al. (2000). The black solid line represents linear regressions derived solely from red *Noctiluca* data (Tada et al., 2000), with the regression equations shown in the figures. Green *Noctiluca* data points are included for comparison purposes only.

GF/F filter for carbon and nitrogen analyses at this site ($n = 4$). In 2010, at all sites, the cellular carbon and nitrogen contents of green *Noctiluca* were measured by collecting approximately 400 cells using a GF/F filter ($n = 2$–5).

Samples for carbon and nitrogen analyses were freeze-dried and analyzed using a CHN analyzer (JM10; J-Science Lab, Japan). A collection of approximately 300 green *Noctiluca* cells yielded about 60 μg of carbon and 9 μg of nitrogen, well above the detection limits of the CHN analyzer (ca. 3 μg for carbon and 1 μg for nitrogen).

3. Results

3.1 Cellular characteristics of green *Noctiluca*
The total Chl-*a* contents in surface waters in 2008 fluctuated between 5.3 and 19.4 μg L^{-1}, with the highest value recorded at Site W31. The green *Noctiluca* cell density in the same year ranged from 230 to 1,033 cells L^{-1}, with the maximum values at Site W31 (Table 1).

Detailed measurements of cellular composition were conducted at Site W31. The carbon content was found to be 556 $\pm$ 96 ng-C cell^{-1} (mean $\pm$ SD, $n = 10$), while nitrogen content was 41 $\pm$ 12 ng-N cell^{-1} ($n = 10$), resulting in a C:N ratio of 16.7 $\pm$ 3.7 mol mol^{-1}. Microscopic analysis revealed a mean cell diameter of 530 $\pm$ 89 μm ($n = 10$). The mean cellular Chl-*a* content was 9.80 $\pm$ 0.78 ng cell^{-1} ($n = 3$), and the calculated cellular carbon to Chl-*a* ratio was 57.

The total Chl-*a* contents in surface waters in 2010 fluctuated between 2.9 and 15.4 μg L^{-1} across all sampling sites. Green *Noctiluca* cell density ranged from 288 to 1,577 cells L^{-1}, with the maximum values recorded at Site

W33 (Table 1). Cell densities were generally higher than those observed in 2008.

Analysis of the cellular composition during this sampling period showed that carbon content varied from 195 to 506 ng-C cell^{-1}, nitrogen content ranged from 17 to 55 ng-N cell^{-1}, and the C:N ratio fluctuated between 10.5 and 20.3 mol mol^{-1} across all sites.

4. Discussion

4.1 Cellular Chl-*a* in *Noctiluca*
The mean cellular Chl-*a* content of green *Noctiluca* at Site W31 in 2008 was 9.80 $\pm$ 0.78 ng cell^{-1} ($n = 3$). According to Saito et al. (2006), the cellular Chl-*a* content of green *Noctiluca* varies depending on cultivation conditions. They reported contents of 12.6 $\pm$ 5.03 ng cell^{-1} without food vacuoles and 6.05 $\pm$ 3.55 ng cell^{-1} in cells with food vacuoles. Our field measurements fell within the range observed in cultured cells, thus suggesting that green *Noctiluca* in their natural habitat exist in both states, with and without food vacuoles.

However, several factors must be considered when interpreting these aforementioned results. The intracellular Chl-*a* content may vary significantly depending on the light environment and nutritional status of individual cells. Additionally, both Saito et al. (2006) and the present study have focused on individuals with cell diameters of approximately 500 μm. Given that green *Noctiluca* in the inner Gulf of Thailand ranges from approximately 250 to 800 μm (Sriwoon et al., 2008), further investigation is therefore needed to understand how physiological characteristics vary with cell size. Using these measurements, we esti-

mated the contribution of green *Noctiluca* to total Chl-*a* content at each sampling site. These contributions were calculated using the following equations:

$$P_c = (D_s \times C_c)/(T_c \times 1000) \times 100$$

where P_c is the percentage of total Chl-*a* contributed by green *Noctiluca* (%), D_s is green *Noctiluca* cell density (cells L^{-1}), C_c is the mean cellular Chl-*a* content of green *Noctiluca* (9.80 ng cell^{-1}) determined at Site W31 in 2008, and T_c is the total Chl-*a* content in the surface water (μg L^{-1}).

Using these calculations, we assessed the relative contribution of green *Noctiluca* to total Chl-*a* at each sampling site. The contributions varied between 36% and 82%, with a mean of 55% $\pm$ 19% ($n = 5$; Table 1). During our 2008 survey, the maximum cell density was 1,033 cells L^{-1}, observed at Site W31 (Table 1). Red tide events are typically characterized by cell densities exceeding 10,000 cells L^{-1} (Tada et al., 2004), indicating that our observed densities were below the red tide thresholds. However, our results demonstrate that green *Noctiluca* can substantially contribute to the water column Chl-*a* content, even at sub-red tide densities.

4.2 Cellular carbon and nitrogen in green *Noctiluca*

The cellular carbon content in green *Noctiluca* analyzed in this study varied from 195 to 556 ng-C cell^{-1}, with a mean of 324 $\pm$ 202 ng-C cell^{-1} (Table 1, $n = 23$). The nitrogen content ranged from 17 to 55 ng-N cell^{-1}, with a mean of 29 $\pm$ 19 ng-N cell^{-1} (Table 1, $n = 23$). In contrast, red *Noctiluca* showed variations in cellular carbon content from 123 to 627 ng-C cell^{-1}, and nitrogen content from 36 to 232 ng-N cell^{-1} (Tada et al., 2000), indicating that the values obtained in our study were within the ranges observed for red *Noctiluca*.

Variations in the cellular carbon content of green *Noctiluca* appear to be influenced by Chl-*a* content. Tada et al. (2000) demonstrated that the carbon and nitrogen content in red *Noctiluca* increased proportionally with cell diameter. In our dataset, measurements of cell diameter and carbon content for green *Noctiluca* were recorded only at Site W31 in 2008. These data revealed that green *Noctiluca* contained higher levels of carbon than red *Noctiluca* with the same cell diameter (Figure 2). This higher carbon content is likely attributable to the endosymbiont, as suggested by the higher Chl-*a* content. Therefore, green *Noctiluca* biomass likely fluctuates significantly not only due to changes in cell size but also due to the quantity of the endosymbiont.

However, this difference is not necessarily constant. Considering that the cellular Chl-*a* content of green *Noctiluca* varies depending on its physiological state (e.g., feeding status), it can be inferred that the carbon content of green *Noctiluca* also varies with these changes. Therefore, although the difference found in this study represents an

estimate based on field measurements, it contains certain uncertainties, and future research should therefore measure larger sample sizes to achieve more accurate biomass assessments.

Regarding nitrogen content, when comparing cells of the same size, the levels were not higher than in red *Noctiluca* but remained at similar levels (Figure 2). The carbon-to-nitrogen (C:N) ratio in green *Noctiluca* ranged from 7.4 to 25.5, with a mean of 13.8 $\pm$ 4.6 (Table 1, $n = 23$), which is notably higher than that observed in red *Noctiluca* (ranging from 2 to 4, Tada et al., 2000). These results indicate that green *Noctiluca* cells contain less nitrogen than red *Noctiluca*. This discrepancy may be attributed to nitrogen assimilation by the endosymbiont, including the utilization of dissolved inorganic nitrogen present by the endosymbiont. Alternatively, this pattern could be explained by enhanced carbon acquisition rather than by nitrogen depletion. Consequently, green *Noctiluca* may convert the C:N ratio of consumed biomass to a "carbon-enriched" state through photosynthetic carbon fixation. The collapse of green *Noctiluca* blooms releases large amounts of organic matter with higher C:N ratios than red *Noctiluca* into the environment, and the decomposition process of this organic matter is expected to demand more oxygen than that of red *Noctiluca*.

Conflict of interest

None declared.

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