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The influence of ultraviolet radiation on the photosynthetic activity of several red algae from different depths

Miyuki Maegawa*, Masayo Kunieda** and Washiro Kida*

*Laboratory of Phycology, Faculty of Bioresources, Mie University, kamihama 1515, Tsu, Mie, 514 Japan
**Toukai Technology Center, Inokoishi 2–710, Meitou-ku, Nagoya, 465 Japan.

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Influence of UV (ultraviolet) radiation on the photosynthetic activity of several red algae collected from the shallow and deep waters was studied. Additionally, light environment in the coastal waters was determined. Direct sun light including PAR (photosynthetically active radiation) and UV radiation had a little effect on the photosynthetic activities of shallow-water species. They seem to be adapted to strong solar radiation and resist UV radiation. Direct sun light for only 30 minutes at noon on a fine day was a serious obstacle to the photosynthesis of deep-water species from the depth of about 25 m. UV radiation amounting to only 1–5% of solar radiation may seriously inhibit the photosynthetic activity of deep-water species used in this study. UV radiation from the sun can be regarded as one of the most important factors limiting the vertical distribution of red algae.

Key Index Words: PAR—photosynthesis—Rhodophyta—solar radiation—UV radiation—vertical distribution.

It is generally believed that red algae are adapted to the deep waters. However, there are many species of red algae growing in the shallow waters. The previous studies (Yokohama 1973, Murase *et al.* 1989) indicated a kind of chromatic adaptation among red algae. The shallow-water species seem to be adapted to white light and the deep-water species to green and blue light. The difference of photosynthetic characteristics between shallow- and deep-water species is dependent on phycoerythrin content, which was closely related to the light conditions in growing site. However, several problems have been remained. One of the most important problems is "Why the deep-water species can not grow in the shallow waters?" The deep-water species adapting to dim and blue or green light might be able to grow in high and white light condition.

In this study, our attention was focused on ultraviolet (UV) radiation affecting the algal photosynthetic activity. Interest in the impact of UV radiation on marine organisms has recently increased because of the possible elevation of UV radiation to the earth's surface, which is caused by thinning of the ozone layer in the upper atmosphere (Hofmann 1989). UV radiation is shorter than 400 nm in wavelength, and it is divided arbitrarily into three groups; UV-A (400–320 nm), UV-B (320–280 nm) and UV-C (280–200 nm). In the outer space UV radiation occupies 9 to 10 %, and on the water surface it occupies only 1 to 5% depending on the weather (Fleishmann, 1989). UV-C is absorbed by ozone layer and oxygen in the atmosphere, so UV-C does not reach to the sea surface. UV-A and UV-B are injurious to organisms on the earth (Calkins 1980). We have a hypothesis that UV radiation from the sun acts as one of the factors limiting the vertical distribution of red algae in the coastal ecosystem, i.e. shallow-water species have an ability to resist strong sun light and UV radiation, in contrast deep-water species do not have such an ability.

There are several studies which have examined the sensitivity for phytoplanktons to

UV radiation (Lorenzen 1979, Smith and Baker 1980, Hobson and Hartley 1983, Bühlmann *et al.* 1987). There was no doubt that increasing UV radiation could depress the photosynthetic activity by bleaching or altering the composition of photosynthetic pigments (Häder and Häder 1988, El-Sayed *et al.* 1990). However, there have been no information on the effects of UV radiation on macroalgae, which play an important role in the coastal ecosystem. In the present paper we have conducted a measurement of UV flux in the coastal water, and estimation of the influence of various intensities of direct sun light, photosynthetically active radiation (PAR) and UV radiation from the sun on photosynthetic activity of red algae from different depths.

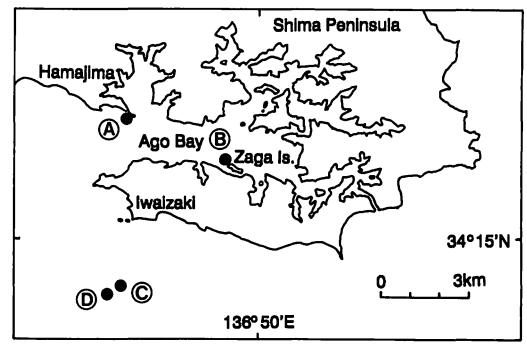

Fig. 1. A map showing the stations where the materials were collected. *Chondrus verrucosa* and *Phyllymenia sparsa* were collected from near the low water level at the point A, and *Gracilaria textorii* from a floating buoy from the point B. *Meristotheca papulosa* and *Peyssonnelia caulifera* were collected at the depth of about 25 m at the point C. At the point D the vertical profile of solar energy spectra were determined.

Materials and Methods

UV radiation above the water surface and in water was measured by Maycum underwater UV sensor (UV103AB). The detection band of this sensor is from 250 nm to 410 nm, and have high sensitivity more than 80% at the range of UV-A and UV-B. PAR above the water surface and in water was measured by LI-COR LI-192SB. These light data were stored in LI-COR LI-1000 data logger. The energy spectrum above the water surface and in water from 300 nm to 1000 nm was measured by LI-COR LI-1800UWC. The light measurements were carried out near the mouth of Ago Bay as shown in Fig. 1.

Five species of the Rhodophyceae were used in this study. Three of them were collected from the shallow waters and the other species were from the deep waters. The former three are regarded as shallow-water species since they can not be found in the deep waters, while the latter two as deep-water species since they can not be found in the shallow waters. The shallow-water species were *Chondrus verrucosa* Mikami and *Phyllymenia sparsa* (Okamura) Kylin collected from near the low water level at the coast of Hamajima and *Gracilaria textorii* Sringer from floating buoy used for pearl oyster cultivation near Zaga Island in Ago bay. The deep-water species were *Meristotheca papulosa* (Montague) J. Agardh and *Peyssonnelia caulifera* Okamura collected from the depth of about 25 m off Iwaizaki.

Collected samples were transported to the Fisheries Research Laboratory of Mie University in Zaga Island and were rinsed with filtered sea water to make them free of obvious epiphytes with careful handling not to wound the fronds and were protected from direct sun light. Sample pieces of 15 cm^2 (3 cm × 5 cm) were cut off fronds, and were kept in running sea water overnight to avoid abnormal results caused by cutting (Sakanishi *et al.* 1988).

Fig. 2 shows schematic diagrams of exposure examination under direct sun light and PAR for shallow- and deep-water species. A piece of sample was set in the water bath in which fresh sea water was poured continuously. Samples were separated into the two groups, which were exposed to direct sun light and PAR respectively. The PAR exposure was made by shielding the sample with an acrylic plate of 3 mm thick, cutting the UV band less then 350 nm in wavelength as shown in Fig. 3. Regulations of the light intensity were served by the sheets of black mesh nets covered in piles. One sheet of the

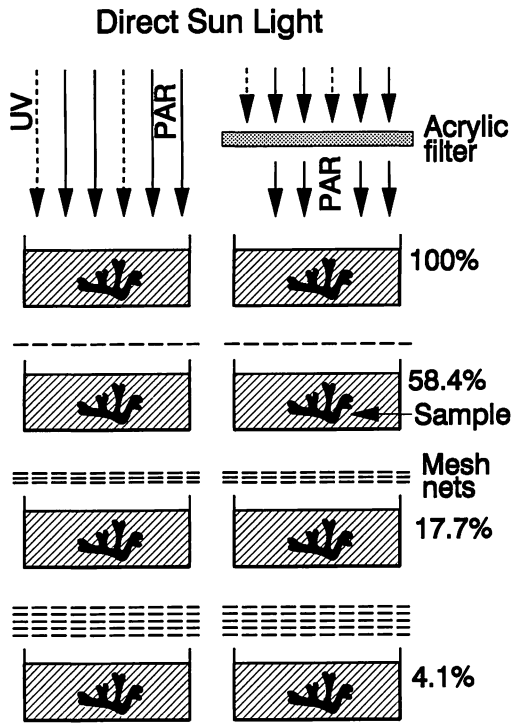

Fig. 2. Schematic diagram of exposure examination under the various intensity of direct sun light and PAR for shallow and deep-water species. Acrylic filter cuts UV radiation and transparent only PAR. Dosage of direct sun light and PAR were regulated by the number of black mesh nets covered in piles and by the exposure period. Relative values of the light intensity are also shown.

net transmitted the light of 58.4%. Samples of *Meristotheca papulosa* and *Phyllymenia sparsa* shielded with 0-5 sheets of black mesh nets were exposed to direct sun light and PAR for 1 and 2 hours, respectively. The samples of *Chondrus verrucosa* shielded with the black mesh nets were exposed for 2 hours, and only the samples under direct sun light and PAR with no black mesh net exposed for 6 hours. This examination was carried out at noon on a fine and sometimes cloudy day in June 19, 1989. During this examination photon flux density ($\mu Em^{-2}s^{-1}$) was monitored and conversed to the unit of integrated photon flux density (Em^{-2}). Therefore, the dosage of photon flux density was regulated by changing the exposure period and the number of black mesh nets. After exposure examination, photosynthetic activities were measured

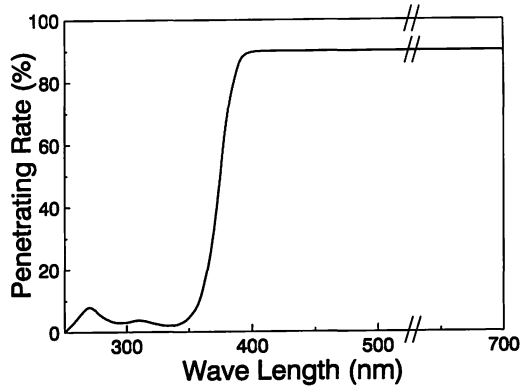

Fig. 3. Transmission spectrum of acrylic plate of 3 mm thick from 250 to 700 nm in wavelength used in the exposure examinations.

at 400 $\mu Em^{-2}s^{-1}$ with the Productmeter, an improved type of differential gas-volumeter (Yokohama *et al.* 1986, Yokohama and Maegawa 1988).

Further exposure examination was designed

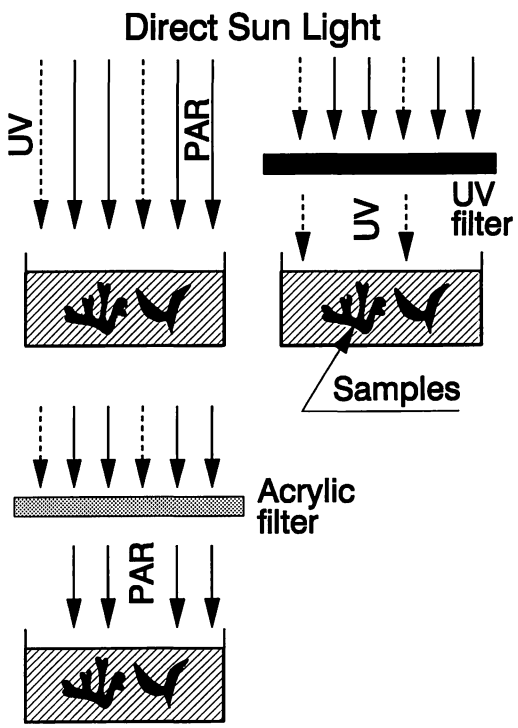

Fig. 4. Schematic diagram of exposure examination under direct sun light, PAR and UV radiation. Acrylic filter cuts UV radiation and UV filter cuts PAR and transparent only UV radiation. Both of shallow- and deep-water species are put in each water bath.

as shown in Fig. 4. Solar radiation was divided into the two bands of UV radiation and PAR by using a UV transmittance filter (Corning 7-54) and the acrylic plate. The Corning 7-54 filter almost cuts PAR longer than 400 nm, and transmitted only UV radiation of 240-400 nm. Three sets of the exposure experiments, direct sun light, PAR and UV radiation, were served by the same way as mentioned in Fig. 2. Each set in the examination included two species of red algae, *Gracilaria textorii* as a shallow-water species and *Peyssonnelia caulifera* as a deep-water species. Each of samples was exposed for 30 minutes at noon on a fine day. During this examination photon flux density and UV radiation were monitored. The amounts of dosage were 200 Whm^{-2} for direct sunlight, 1.5 Em^{-2} or 100 Whm^{-2} for PAR and 9 Whm^{-2} for UV radiation. The radiometric units (Whm^{-2}) of direct sun light and PAR were conversed by the manual of LI-COR (1979). This exposure examination was carried out in June 21, 1990.

After exposure examination, photosynthesis and respiration were measured by the Productmeter at 8 different intensities from 0 to 400 $\mu Em^{-2}s^{-1}$ of artificial light and at 24.5°C, which was near the *in situ* sea water temperature of sampling area. The light source was a projector lamp (Kondo 100 V-300 W) and the light intensity was adjusted using neutral density filters (Toshiba TND-50, -25, -12.5). Photon flux density was measured with a quantum meter system (LI-COR LI-192SB, LI-1000). UV radiation from the projector lamp is assumed to be cut by the bottom of the water bath made of acrylic plate. Photosynthetic and respiratory rates were measured in the same manner as we used in our previous experiment (Murase *et al.* 1989).

Results

Fig. 5 shows a vertical profile of solar energy spectra from 300 nm to 1000 nm in wavelength at a point near the sampling station of deep-water species off Iwaizaki at noon on a fine day in July 22, 1992. When the sun light penetrates the ocean it is altered in both quality and quantity. Water itself absorbs strongly the component above 600 nm including red light, far red and infrared radiation. UV radiation below 400 nm and blue light in shorter part were attenuated strongly by the water and suspended matters. So, in the deep waters blue to green light from 450 nm to 600 nm occupied a large part of light energy. The maximum transmittance can be seen at around 500 nm in this area.

Fig. 6 shows a typical vertical profile of UV radiation below 400 nm and PAR from 400 nm to 700 nm calculated from the data of Fig. 5. Attenuation rate of UV radiation was higher

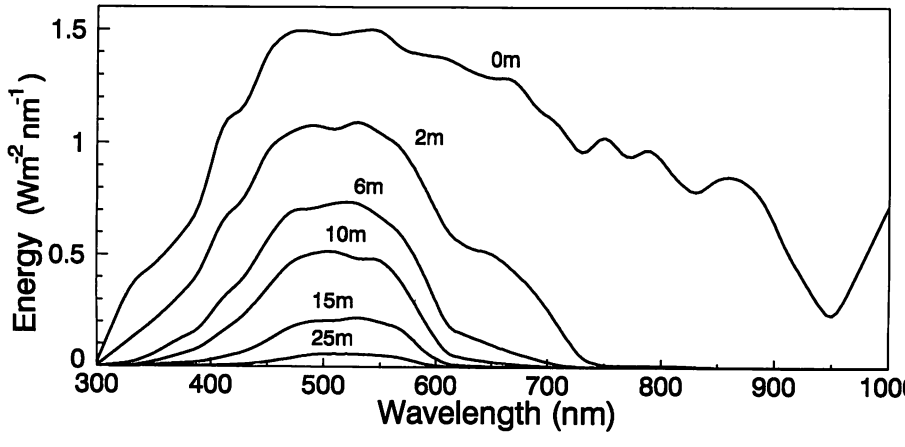

Fig. 5. Vertical profile of solar energy spectra from 300 nm to 1000 nm in wavelength at a point near the sampling station for deep-water species.

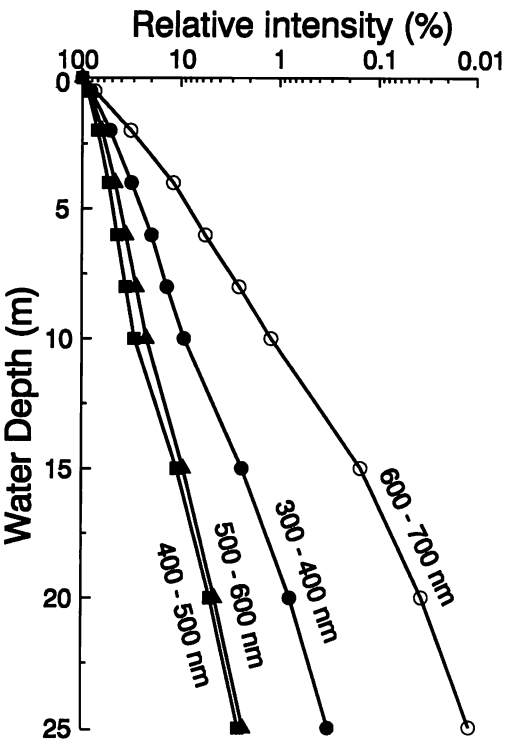

Fig. 6. Vertical profile of UV radiation and PAR calculated from the data in Fig. 5. Each line shows the average value of 300–400 nm (-●-), 400–500 nm (-■-), 500–600 nm (-▲-) and 600–700 nm (-○-).

than PAR from 400 nm to 600 nm, and was lower than red light from 600 nm to 700 nm. UV radiation decreased to about 11% at 10 m and to below 1% at 20 m in depth.

Effects of the pre-exposure to different amounts of direct sun light and PAR on the photosynthetic activity of shallow- and deep-water species were shown in Fig. 7. *Chondrus verrucosa* from the lower level of intertidal zone decreased in photosynthetic activity gradually with increasing in direct sun light and PAR, and maintained about 50-65% after exposure to 9 Em^{-2} of PAR or direct sun light, which corresponded to exposure to direct sun light for 6 hours about noon on a fine day in summer. The photosynthetic activity of *Phyllymenia sparsa* from the upper level of sublittoral zone decreased to 30% and 22% after exposure to 6 Em^{-2} of PAR and direct sun light, respectively. Shallow-water species were a little more sensitive to direct sun light containing UV radiation than PAR. As compared with the shallow-water species, enhanced solar radiation greatly reduced the photosynthetic activity of a deep-water species, *Meristotheca papulosa*, collected from 25 m in depth. After exposure to 1 Em^{-2} of PAR, the photosynthetic activity of *M. papulosa* maintained 78% under PAR, and decreased to only 16% under direct sun light. After exposure to about 2 Em^{-2} of PAR, the photosynthetic activity of this species was lost.

Figs. 8 and 9 show the photosynthesis-light curves of a shallow-water species, *Gracilaria textorii*, and a deep-water species, *Peyssonnelia caulifera*, respectively, after exposure to direct sun light, PAR and UV radiation for 30 minutes as shown in Fig. 4. The photosynthetic activity of each sample showed relative value to the control samples, which was exposed neither to direct sun light nor to UV radiation. Saturated photosynthetic activity of *G. textorii* after exposure to sun light decreased to 75-80% of control samples as shown in Fig. 8. There is also no marked difference in the photosynthetic-light curves among samples exposed to direct sun light, PAR and UV radiation, besides a slightly gentle initial slope of the sample exposed UV radiation. As for the deep-water species *Peyssonnelia caulifera* in Fig. 9, decreases in the saturated photosynthetic activity and the angle of intial slope in the photosynthesis-light curve of the sample exposed to direct sun light, PAR or UV radiation were more pronounced than those observed in the shallow-water species. Direct sun light was the most injurious to deep-water species, and depressed the saturated photosynthetic activity to only 5-10% of that in the control after exposure to 1.5 Em^{-2} of PAR. Enhanced UV radiation and PAR alone also affected the photosynthetic activity of *P. caulifera*, and depressed the saturated photosynthetic activity of this species to 50-60% and 20-30%, respectively.

Discussion

Numerous studies have shown that increasing levels of UV exposure result in reducing

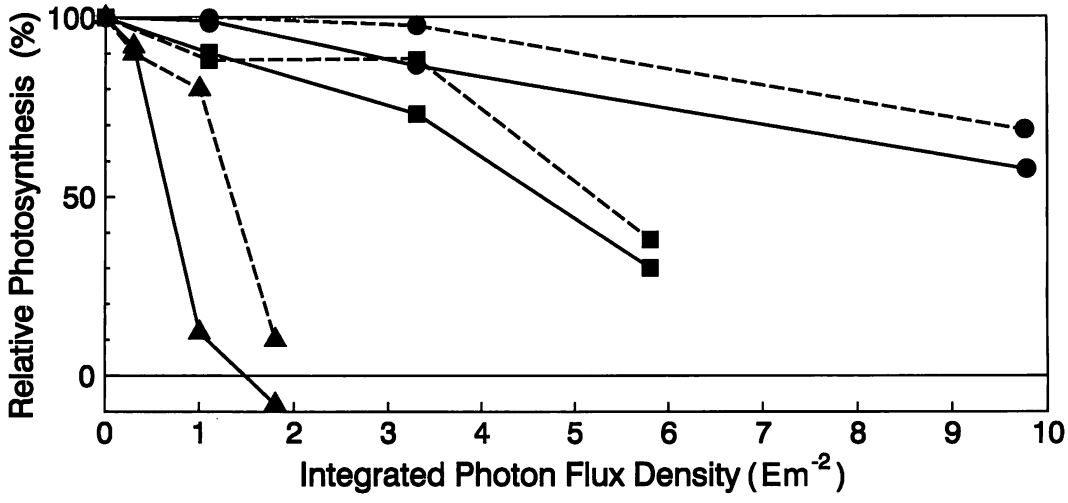

Fig. 7. Changes in photosynthetic activity after exposing to direct sun light and PAR. Dosage of direct sun light and PAR was adjusted by changing the exposure period and the number of black mesh nets (cf. Fig. 2). After the exposure examination, photosynthetic rate was mesured at 400 μEm^{-2}s^{-1}. Samples were *Condrus verrucosa* (●) collected from intertidal zone, *Phyllymenia sparsa* (■) collected from upper subtidal zone and *Meristotheca papulosa* (▲) collected from depth of 25 m. Straight lines and broken lines show the data under direct sun light and PAR, respectively.

primary production of phytoplanktons (Steeman-Nielsen 1954, Calkins 1980, Worrest *et al.* 1980, Hobson and Hartley 1983, Bühlman *et al.* 1987). Bülmann *et al.* (1987) pointed out that there was no photoinhibition without UV or under weak UV radiation, and under more than 70 μEm^{-2}s^{-1} of UV radiation photoinhibition is always observed to a certain degree depending on the combination of PAR and UV ray on phytoplanktonic C-assimila-

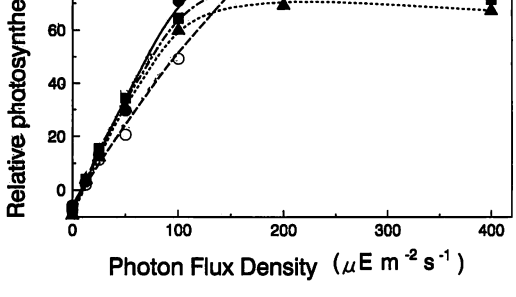

Fig. 8. Photosynthesis-light curves of *Gracilaria textorii*, a shallow-water species determined, after exposing to direct sun light (-▲-), PAR (-■-) and UV radiation (-○-) for 30 minutes at noon on a fine day in summer (cf. Fig. 4). Photosynthetic activity was shown in relative values against data obtained with the control sample's data kept in a running seawater bath without exposing to direct sun light (-●-). Dosage of direct sun light for 30 minutes at noon on a fine day corresponded to 1.5 Em^{-2} or nearly 100 Whm^{-2} of PAR, and 9 Whm^{-2} of UV radiation.

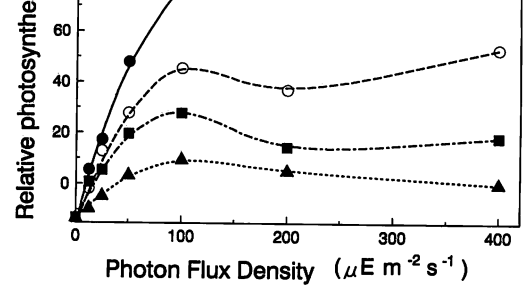

Fig. 9. Photosynthesis-light curves of *Peyssonnelia caulifera*, a deep-water species determined after exposing to direct sun light (-▲-), PAR (-■-) and UV radiation (-○-) for 30 minutes at noon on a fine day in summer (cf. Fig. 4). Photosynthetic activity was shown in the relative values against data obtained with the control sample kept in a running seawater bath without exposing to direct sun light (-●-). Dosage of direct sun light for 30 minutes at noon on a fine day corresponded to 1.5 Em^{-2} or about 100 Whm^{-2} of PAR, and 9 Whm^{-2} of UV radiation.

tion. Also, Jokiel and York (1984) observed that photosynthetic activities of phytoplanktons in the shallow waters had an ability to resist strong UV radiation, and deep-water species did not have such an ability. The results obtained in the present study on macroalgae were essentially similar to those observed in phytoplanktons.

The photosynthesis of the deep-water species was seriously inhibited by the exposure to direct sun light for only 30 minutes at noon on a fine day in summer, while that of the shallow-water species was little affected. A considerable part of the inhibition on the photosynthesis of the deep-water species seems to attribute to UV radiation, which amounts to only 4–5% of direct sun light at noon on a day in summer. However, the effect of PAR on the photosynthesis of the deep-water species was larger than that of UV radiation as shown in Fig. 9. This fact suggests that the mechanism of the photoinhibition on deep-water red algae is different from that of the photoinhibition on phytoplankton since Bühlmann *et al.* (1987) pointed out that there was no photoinhibition without UV radiation in phytoplankton.

Although the total effect of PAR in the inhibition on the photosynthesis of the deep-water species was larger than that of the UV radiation, the specific effect of UV radiation was much larger than that of PAR. In the case of the shallow-water species, the specific effect of UV radiation was not so larger than that of PAR. It can be assumed that shallow water red algae possessed strategies to cope with UV radiation. Several authors pointed that UV absorbing substance contained in some algae played an important role as a biofilter against the solar UV radiation (Shibata 1969, Sivalingam and Nisizawa 1990). In fact, this substance is contained in almost of all groups in algae, particularly much in red and blue-green algae. Whereas, the deep-water red algae used in this study had little ability to resist the surplus direct sun light and UV radiation. This fact suggests that the deep-water species have a little or no UV absorbing substance. Further investigation on the UV absorbing substance will be carried out in a next research.

The previous papers (Yokohama 1973, Murase *et al.* 1989) indicated that one of the most important factors limiting vertical distributions of red algae was the vertical variation in light intensity and spectral properties. From the results of the present study, however, it is assumed that the intensity of UV radiation is another most important factor limiting vertical distributions of red algae. About 11% of UV radiation at the water surface penetrated to the depth of 10 m at a point near the station where the deep-water species were collected (Figs. 5 and 6). This fact indicates that the photosynthesis of the deep-water species is seriously inhibited by the exposure to under-water light at the depth of 10 m for 4.5 hours at noon on a fine day in summer. The excessive UV radiation in the shallow waters may function as the most important factor determining the upper limit in the vertical distribution of a red alga.

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前川行幸*・国枝昌代・喜田和四郎*：紫外線が生育深度の異なる紅藻の光合成におよぼす影響**

浅所から採集された3種の紅藻および深所（水深約25 m）から採集された2種の紅藻について，UV（紫外線）が光合成活性におよぼす影響を調べた。また，沿岸域での光環境も合わせて測定した。PAR（光合成有効波長域）や紫外線を含む太陽からの直射光による前照射は，浅所産紅藻の光合成活性をほとんど低下させることがなかったのに対し，深所産紅藻は夏の晴天の正午前後30分間の直射光，そのPAR成分およびUV成分のいずれの照射によっても著しい光合成活性の低下が見られた。海面上で太陽放射の1–5%を占めるすぎない紫外線が深所産紅藻の阻害作用に占める割合はかなり大きいものといえるが，PARとUVの相乗効果は深所紅藻の光合成活性をさらに大きく低下させるものと考えられる。水中の光環境の測定から，5–10 mの水深に到達するUVの量は深所産紅藻の光合成に障害をおよぼすに十分であるとみなされ，したがって，本研究に用いられた深所産紅藻はこのような浅所では生育できないものと考えられる。紫外線は紅藻の垂直分布を規制する大きな要因の一つであると言えよう。（*514 三重県津市上浜町1515　三重大学生物資源学部藻類増殖学研究室，**465 名古屋市東区猪子石2-710　㈶東海技術センター）

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