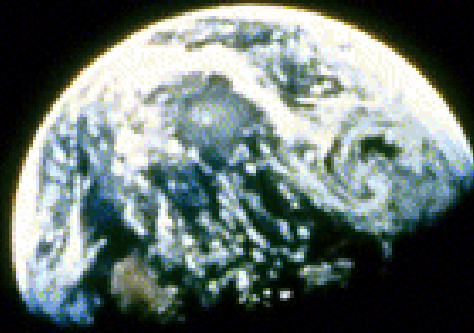
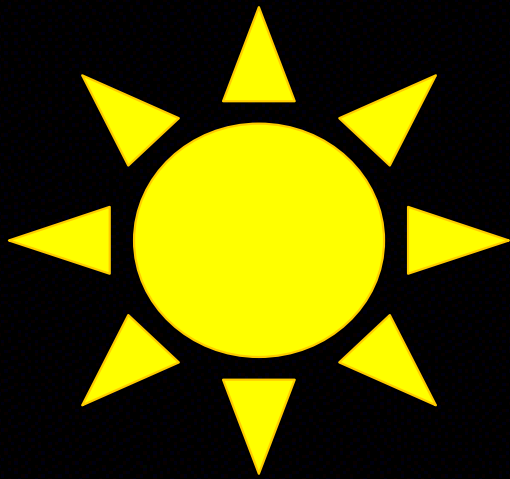
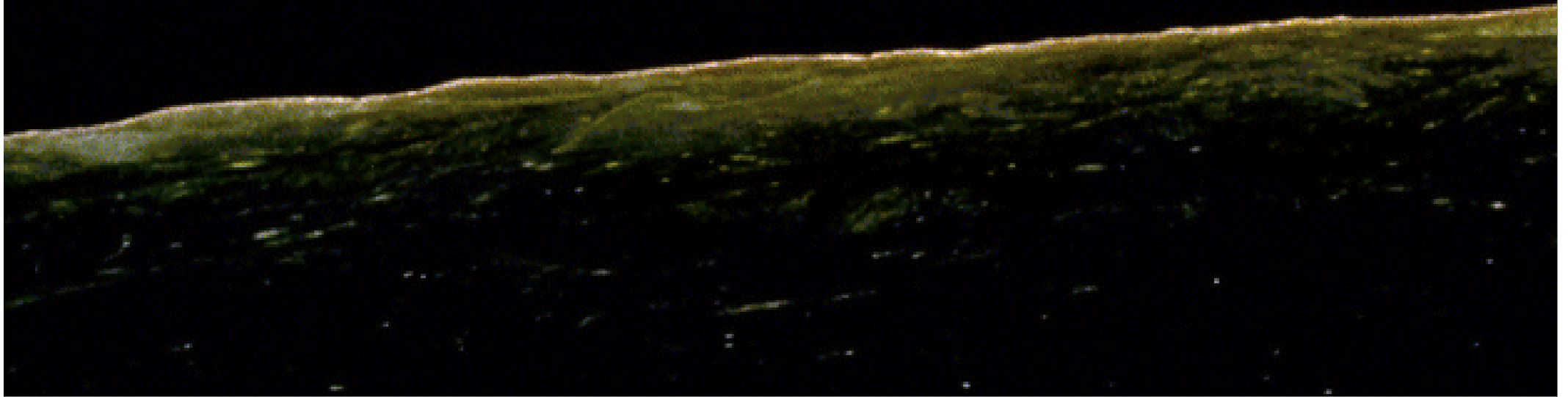




LIGHT

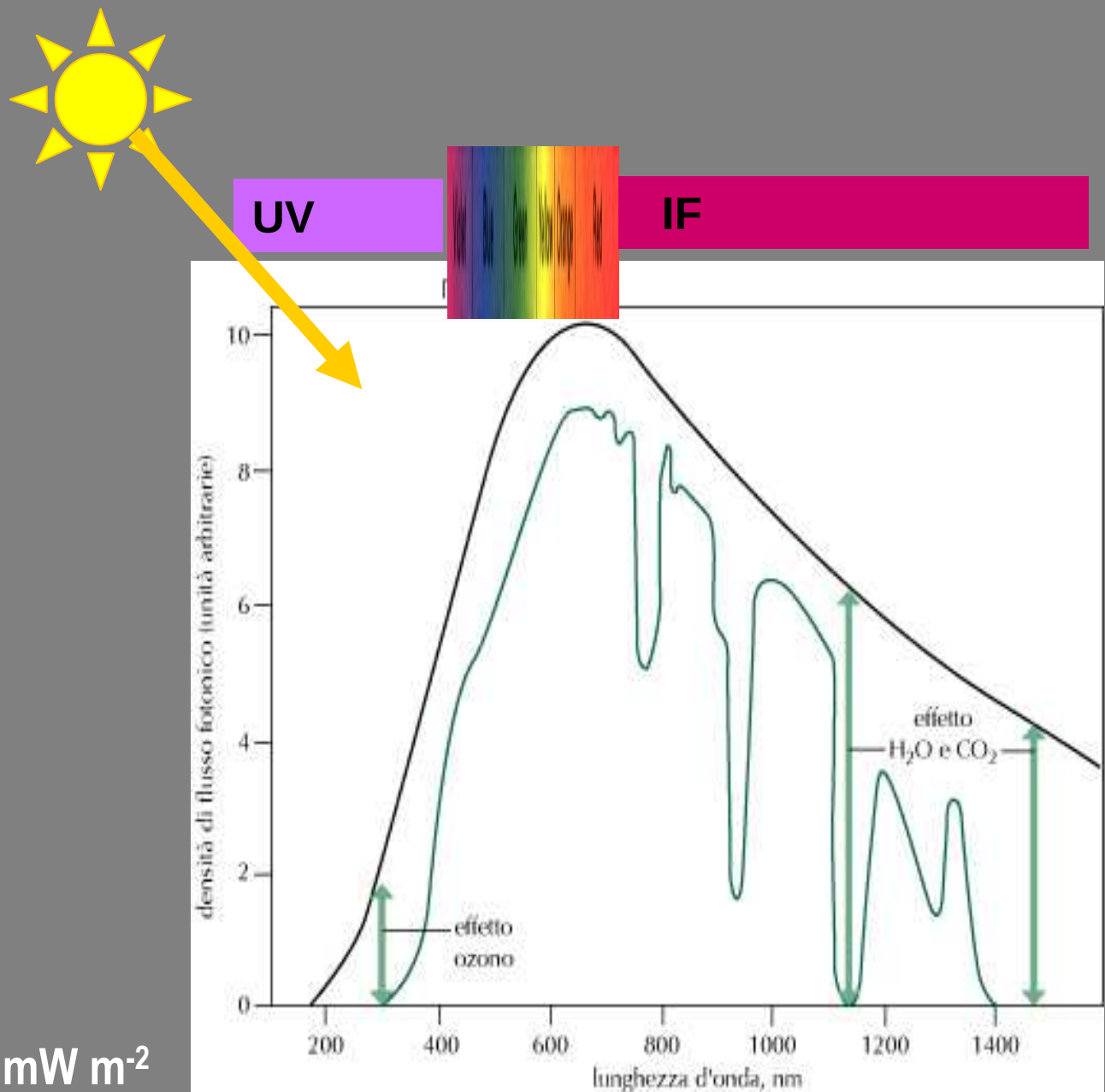


Solar radiation

Bright sunshine in the visible range (400-700 nm) and at the surface of the Earth is about 500 W m^{-2}



Moonlight on a clear night is 1 mW m^{-2}



$$E = h\nu = hc/\lambda$$

Visible light
(400-700 nm)
is absorbed by
photosynthetic pigments

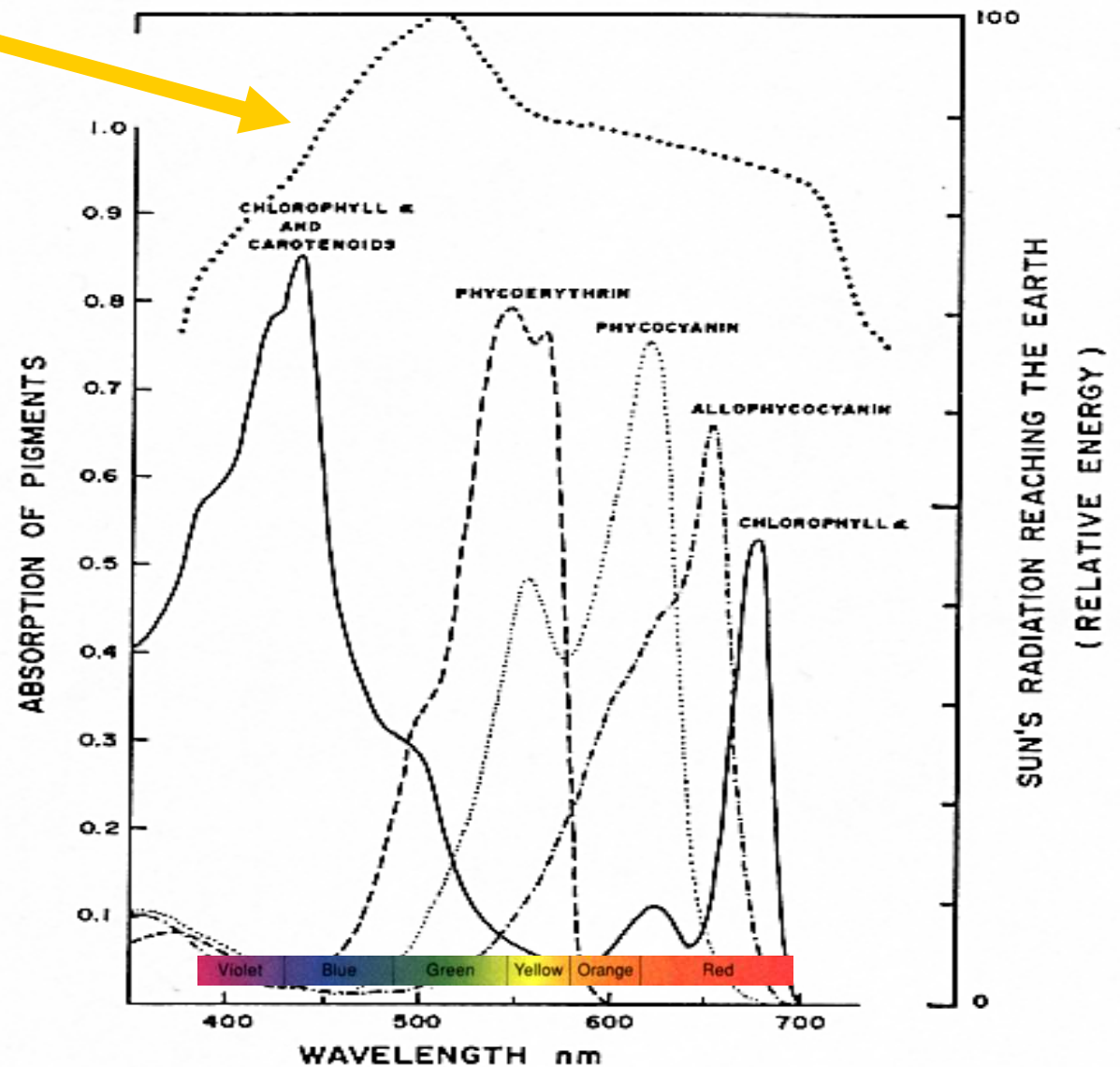
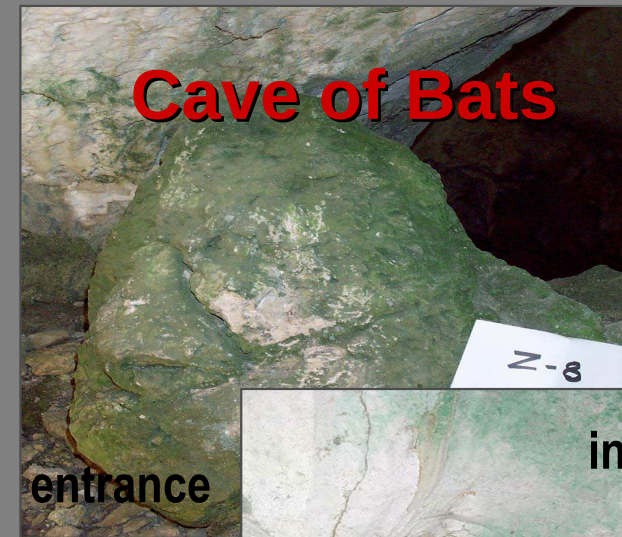


Figure 4.1. Spectrum of solar energy at the earth's surface (upper dotted curve), and absorption spectra of algal pigments.

Measure of light using a radiometer with a Quantum sensor

Photosynthetic Photon Flux Density – PPFD units:
IRRADIANCE available for photosynthesis (PAR)
equals micromoles quanta per squared meter per
second = $\mu\text{mol photons m}^{-2} \text{ s}^{-1}$



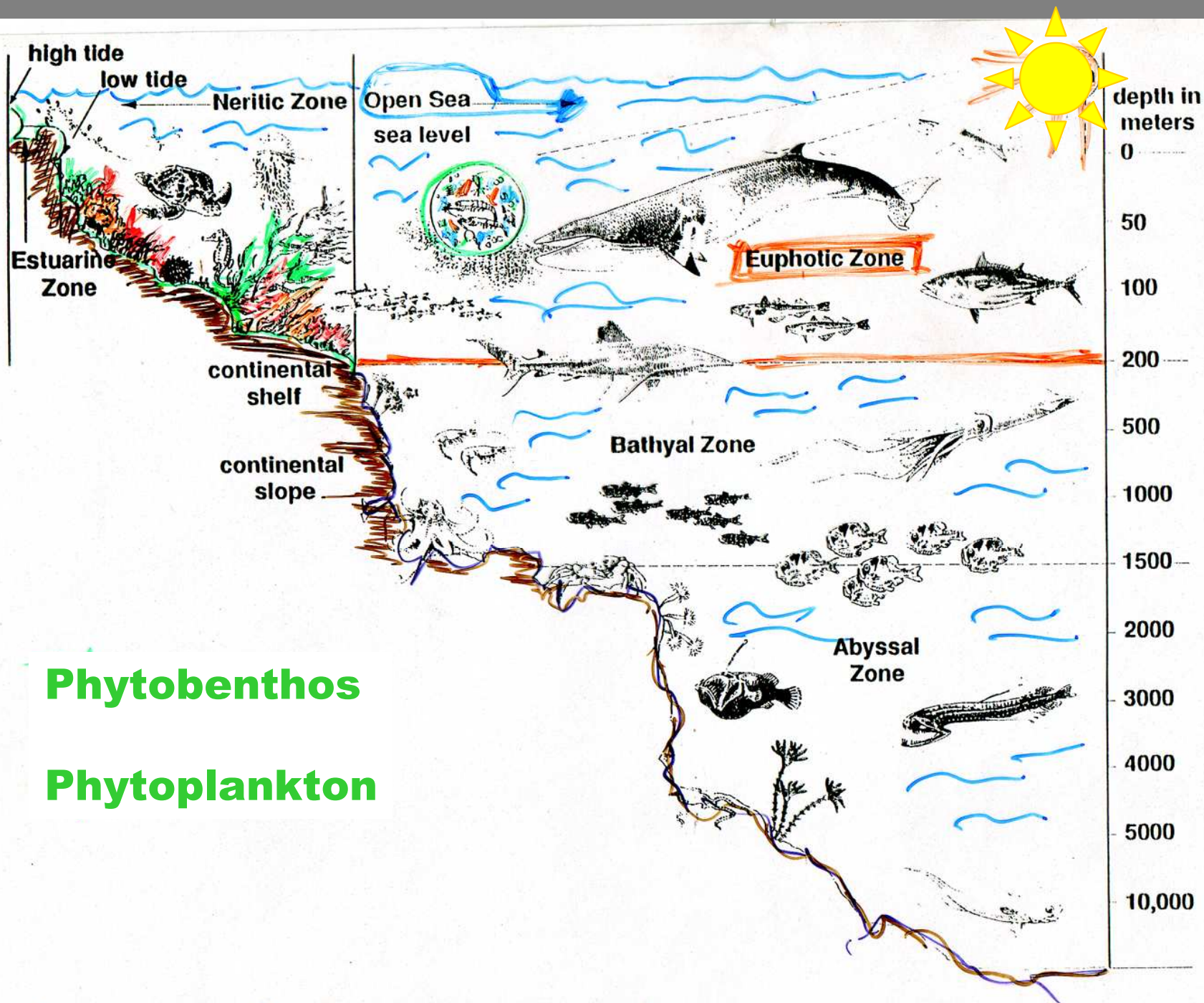
Site	CATS Project				
	Physical parameters				
	Light $\mu\text{mol m}^{-2} \text{ s}^{-1}$	Wm^{-2}	Lux	T $^{\circ}\text{C}$	RH %
Z 1	3 - 18	1.2 - 4.5	200 - 800	14.5	86.0
Z 2	1.0	0.15	48	13.6	93.8
Z 3	0.2 - 0.3	0.02	10 - 15	14.4	85.4
Z 4	0.1 - 0.2	0.03 - .09	10 - 20	13.6	87.0
Z 5	0.05 - 0.15	0.15	18	13.6	83.2
Z 6	4 - 5	0.7 - 1.0	200 - 250	11.0	85.5
Z 7	1.5	1.0	250	8.2	56.0
Z 8	3.8 - 7.4	0.9 - 1.6	260 - 430	8.7	54.0

Solar irradiance in a sunny
day at our latitude is about
 $2000 \mu\text{mol photons m}^{-2} \text{ s}^{-1}$



Photic zone

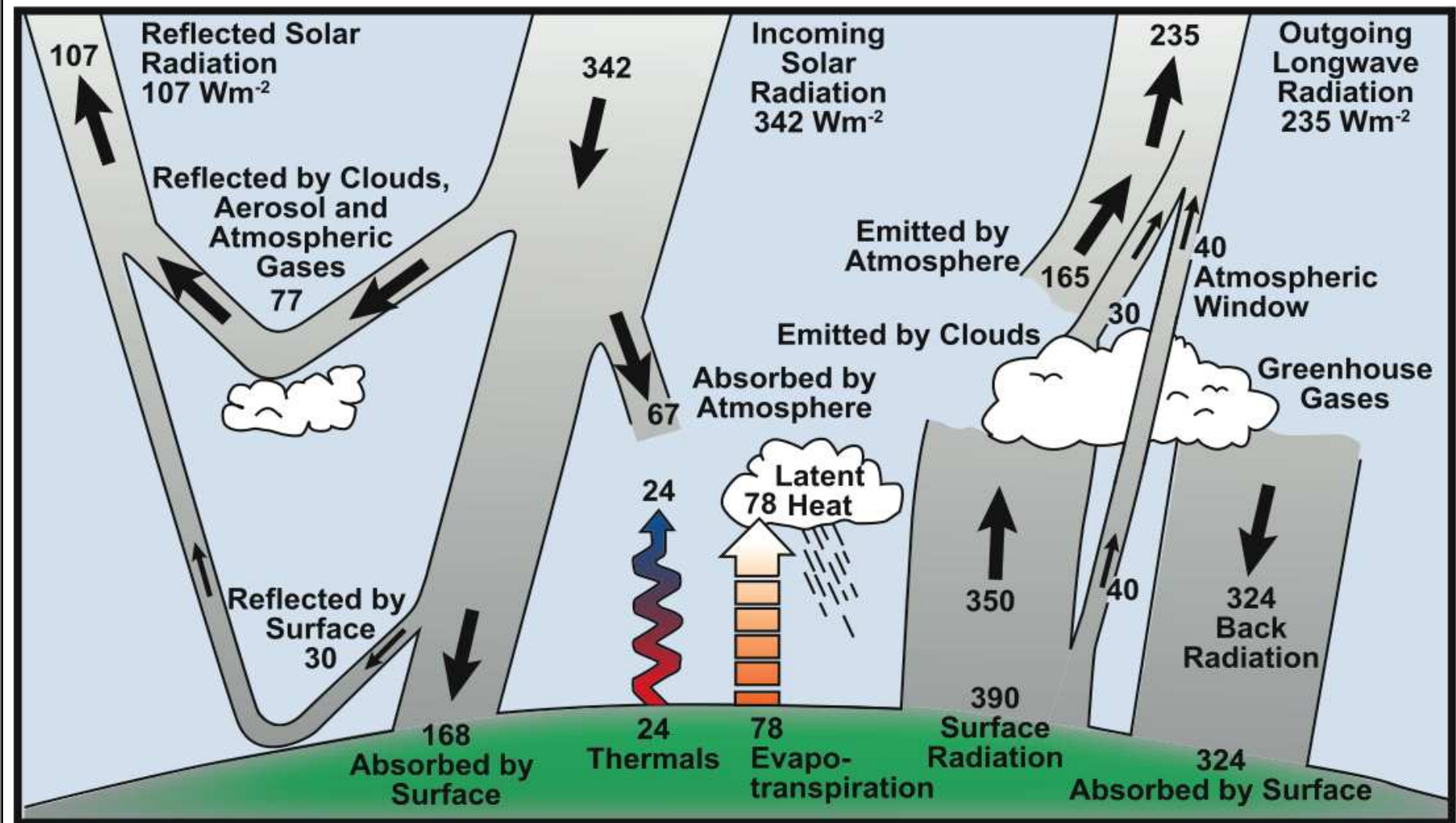
**Underwater
Light**



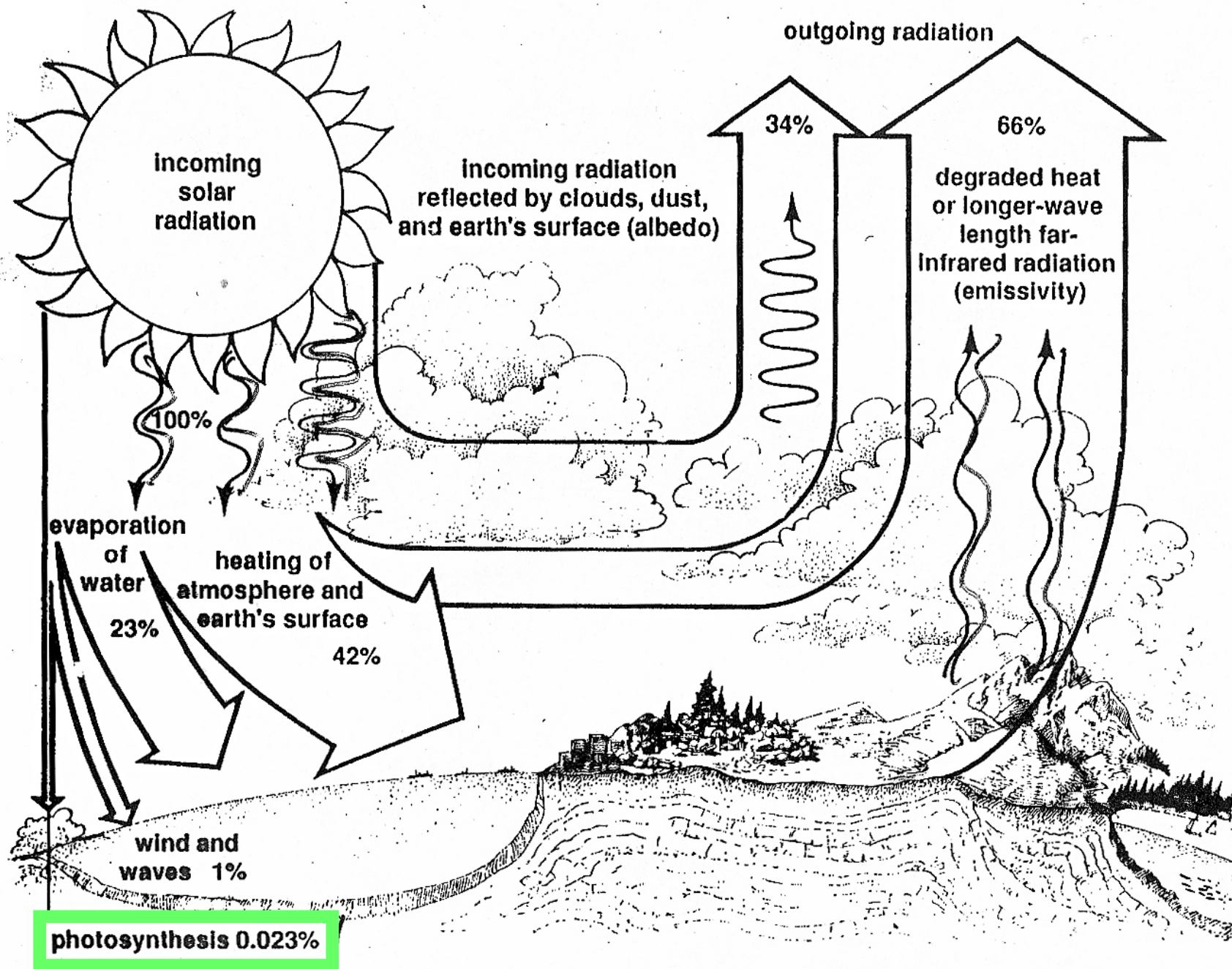
Phytobenthos

Phytoplankton

Major zones of life in a marine ecosystem.



Estimate of the Earth's annual and global mean energy balance. Over the long term, the amount of incoming solar radiation absorbed by the Earth and atmosphere is balanced by the Earth and atmosphere releasing the same amount of outgoing longwave radiation. About half of the incoming solar radiation is absorbed by the Earth's surface. This energy is transferred to the atmosphere by warming the air in contact with the surface (thermals), by evapotranspiration and by longwave radiation that is absorbed by clouds and greenhouse gases. The atmosphere in turn radiates longwave energy back to Earth as well as out to space. Source: Kiehl and Trenberth (1997).



The flow of energy to and from the earth.

Light is reflected by Earth's and water surface

Table 4.1 *Effects of solar altitude and sea state on reflection from the surface*

Condition	Percentage reflectance at solar altitude						
	90–50°	40°	30°	20°	10°	5°	0°
Calm sea	3	4	6	12	27	42	100
Rough sea (Beaufort scale 4)	3	4	6	10	11		

Source: Drew (1983), with permission of Clarendon Press.

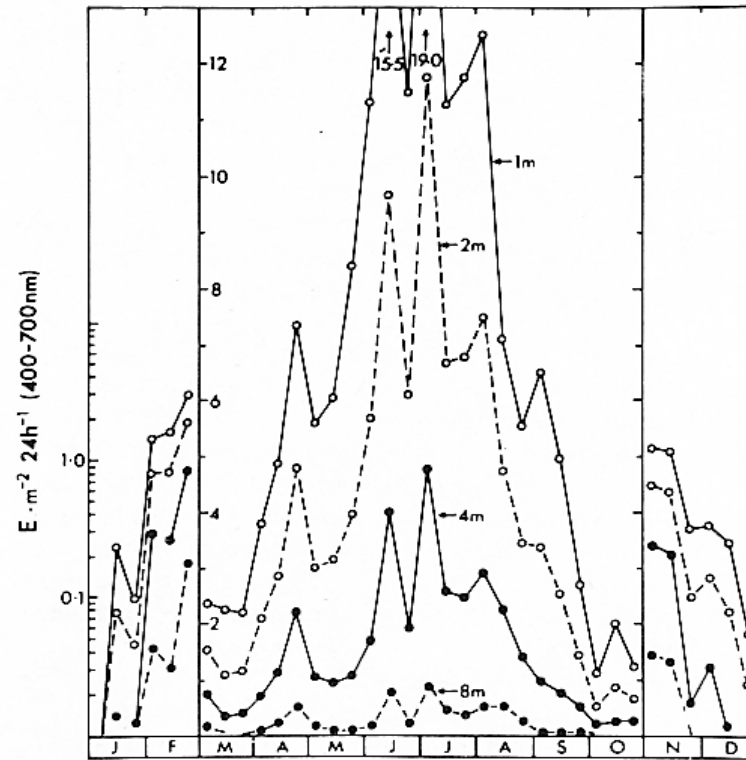
Underwater irradiance :

At a fixed latitude changes are due to:

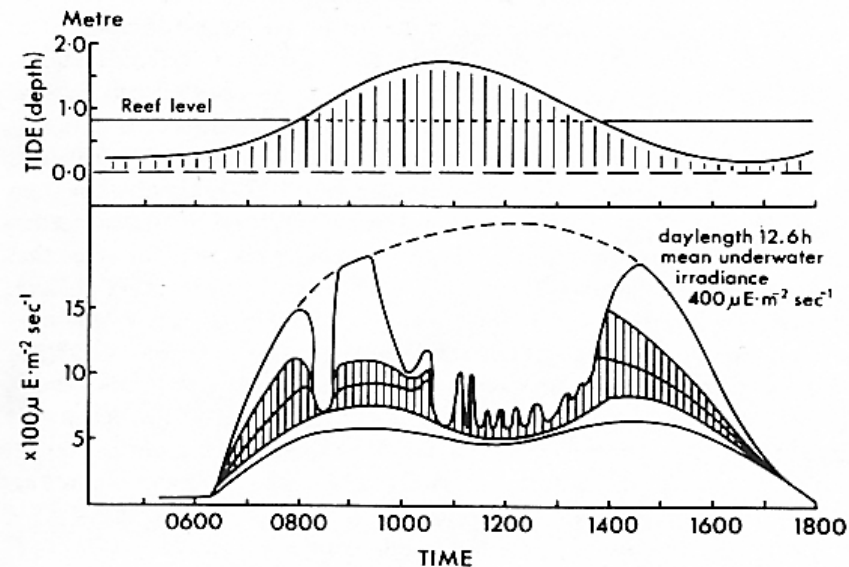
depth (a)

time of the day (b)

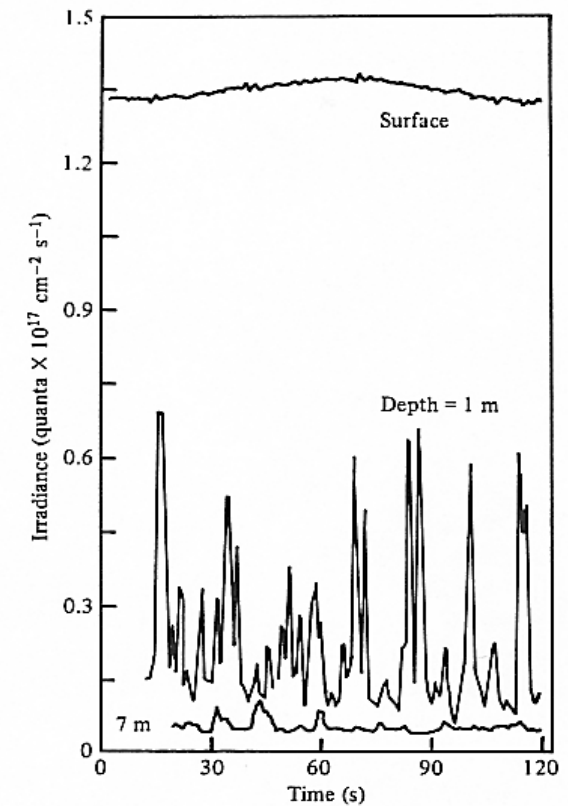
waves (c)



(a)



(b)



(c)

Figure 4.2. Heterogeneity of underwater light at several time scales. (a) Annual variations in PAR at various depths in the North Sea. (b) Diurnal changes in underwater irradiance as a result of solar flux and tide changes at Long Reef, Sydney, Australia. Upper part shows the course of the midday high tide. In the lower part, the upper and lower solid lines show the maximum range of irradiance; the center line is the mean, and the hatched area the 70% range. The broken line shows maximum irradiance on a day with a midday low tide. (c) Momentary changes in irradiance at the surface, at 1 m (in the region of greatest heterogeneity), and at the seabed, 7 m below the surface in a California giant kelp bed.

Light changes in water with depth: decay occurs exponentially with an extinction coefficient that depends on the wavelength of light and the types of material suspended in the water column



extinction coefficient for red and infrared light in pure water is about 2.0 per meter; for blue light it is 0.01 per meter

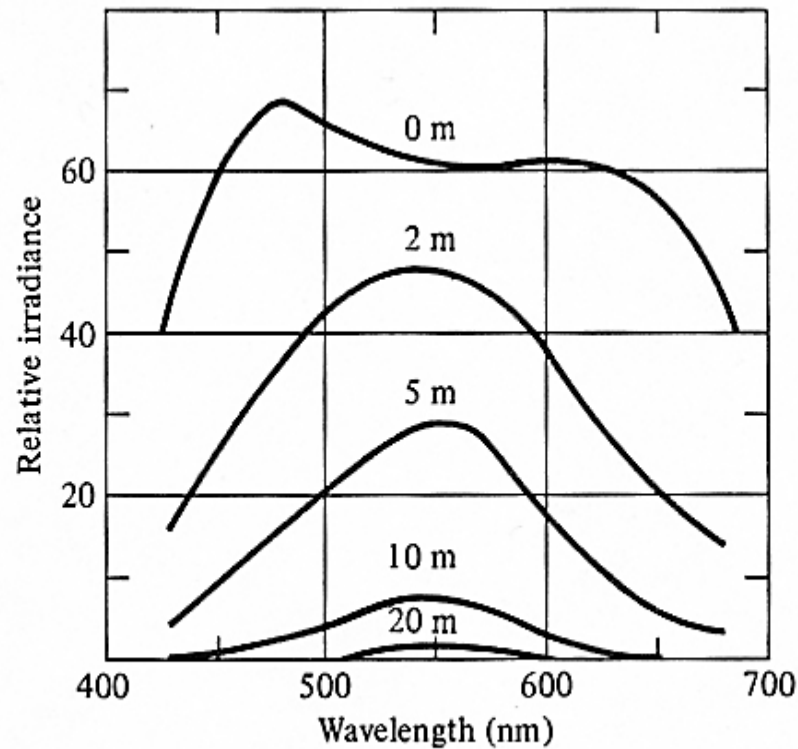


Figure 4.4. Energy spectra of natural light at various depths in the northern Baltic Sea.

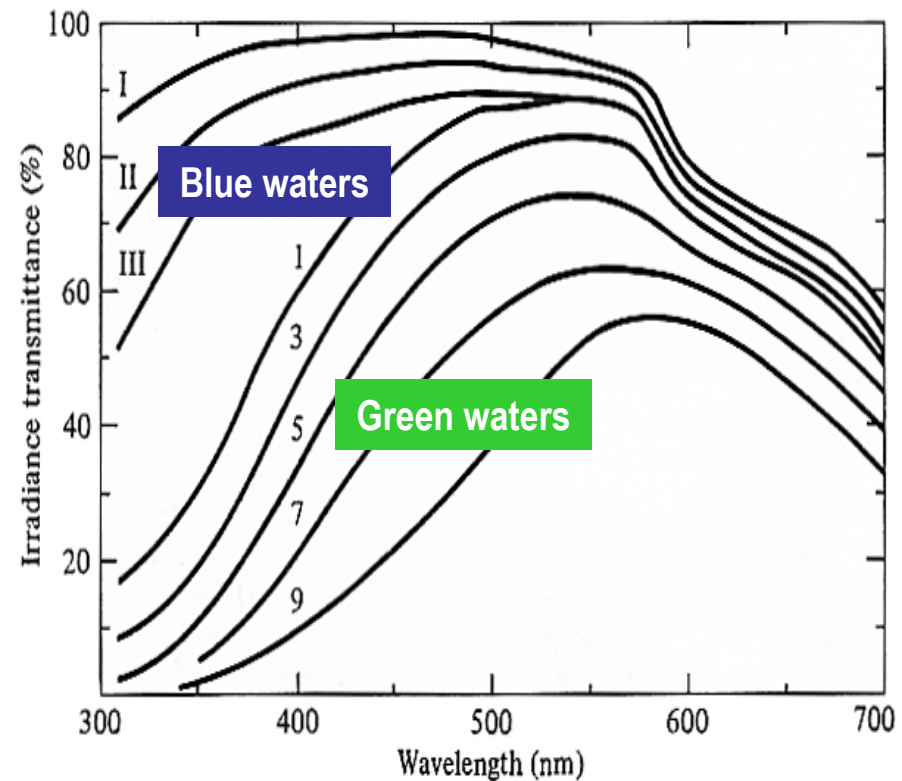


Figure 4.3. Percentages of transmittance downward of irradiance of various wavelengths in Jerlov's different optical types of water. The types range from clear oceanic (type I) to turbid coastal (type 9).

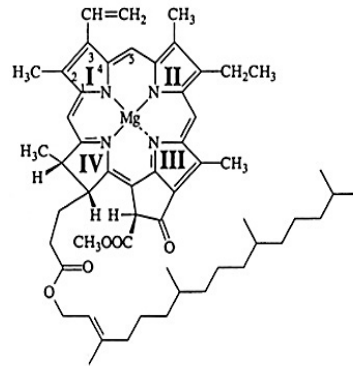
Table 1. Major characteristics of the algal groups and cyanobacteria

Phylum	Chl /PBP	Major Carotenoid	Plastid	Stored food	Cell wall	Flagellar type
Haptophytes	$a+c_1+c_2$	fucoxanthin	3, 4 OMs	c'laminarin	cellulose, alginate	2 equal, smooth
Phaeophytes	$a+c_1+c_2$	fucoxanthin	3, 4 OMs	laminarin	cellulose, alginate	1-2,unequal,hairy
Bacillariophytes	$a+c_1+c_2$	fucoxanthin	3, 4 OMs	laminarin	silica, alginate	Male only: 1 hairy
Chrysophytes	$a+c_1+c_2$	fucoxanthin	3, 4 OMs	c'laminarin	cellulose, silica	1-2,unequal,hairy
Eustigmatophytes	a	violaxanthin	3, 4 OMs	c'laminarin	cellulose,	1-2,unequal,1 hairy
Xanthophytes	$a+c_1+c_2$	heteroxanthin	3, 4 OMs	c'laminarin	cellulose	1-2,unequal,1 hairy
Dinoflagellates	$a+c_2$	peridinin	3, 3 OMs	starch, lipid	cellulose, theca	2,unequal,1 hairy
Cryptophytes	$a+c_2$ +PBP	alloxanthin	2, 4 OMs	starch	absent	2+/- equal, hairy
Chlorarachniophytes	a+b	violaxanthin	2-6, 4OMs	starch	cellulose	lacking
Euglenophytes	a+b	diadinoxanthin	3, 3 OMs	paramylon	cellulose	2-several,hairy
Apicomplexans	none	none	none, 4 OMs	?	none	none
Prasinophytes	a+b (c-like)	violaxanthin	2-6, 2 OMs	starch	cellulose	4, scaly smooth or hairy
Chlorophytes	a+b	siphonaxanthin	2-6, 2 OMs	starch	cellulose	2(4),equal, smooth
Charophytes	a+b	zeaxanthin	many, 2 OMs	starch	cellulose	2 equal hairy or scaly
Glaucocystophytes	a+PBP	lutein	0, 2 Oms +pepidoglycan wall	starch	cellulose/xylan	lacking
Rhodophytes	a+PBP	lutein	0, 2 OMs	flor. starch	cellulose/xylan	lacking
Cyanobacteria	a+PBP	echinenone	none	glycogen	murein	lacking
Cyanobacteria (prochlorophytes)	$a+b\pm c$ -like $\pm$ PBP	echinenone	none		murein	lacking
Cyanobacteria (<i>Acaryochloris</i>)	a+d +PBP	echinenone	none	glycogen	murein	lacking

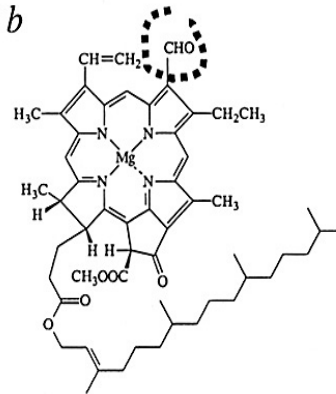
Flor. starch, floridean starch; myx. starch, cyanophycean starch; PBP, phycobiliprotein; OM, plastid envelope membranes; c'laminarin, chrysolammarin. Plastid: the first number refers to the typical number of stacked thylakoids; the second number refers to the number of outer membranes (OM).

Photosynthetic pigments: Chlorophylls

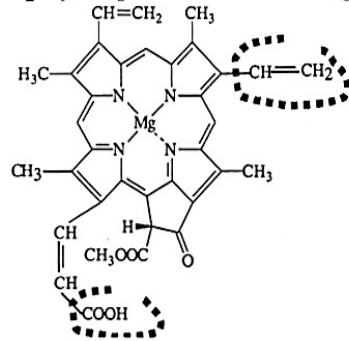
Chlorophyll *a*



Chlorophyll *b*



Chlorophyll *c*₂



Chlorophyll *d*

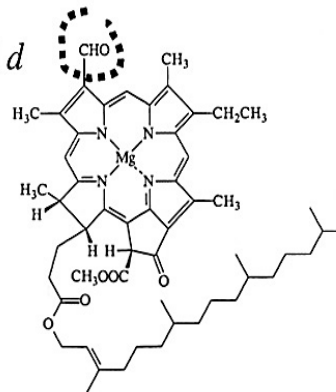


Fig. 1. The structure of the chlorophylls. Characteristic groups of Chl *b*, Chl *c*₂ and Chl *d* are indicated. Note that Chl *c*₁ has an ethyl group in the place of the vinyl group of Chl *c*₂. Note also that the only difference between Chl *b* and Chl *d* is that the formyl group is on Ring I in Chl *d* and on Ring II in Chl *b*.

Relative Absorption

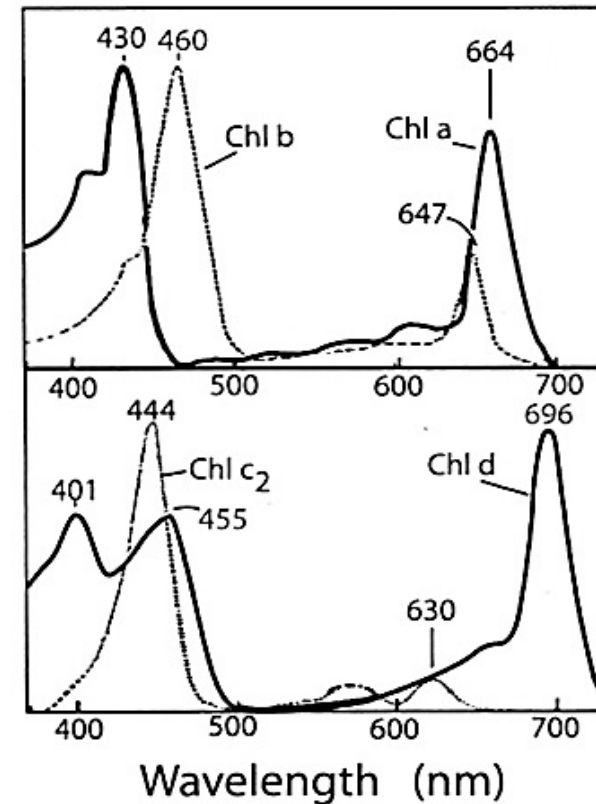


Fig. 2. The absorption spectra of Chl *a*, Chl *b*, Chl *c*₂ and Chl *d* in 90% acetone-water. The peak wavelengths are indicated; note that the peak wavelengths are affected by the solvent used and the concentration of that solvent if diluted with water; in the case of Chl *c* only the wavelengths for Chl *c*₂ are shown: for Chl *c*₁ in 90% acetone-water the peaks are 442 nm and 630 nm. Note that the chlorins (Chl *a*, *b* and *d*) have strong bands in the red region of the spectrum as well as for the Soret (blue) bands, whereas the porphyrins (Chl *c*'s) have a weak band in the red region and only a strong Soret band.

Photosynthetic pigments: Carotenoids (C₄₀ tetraterpenes)

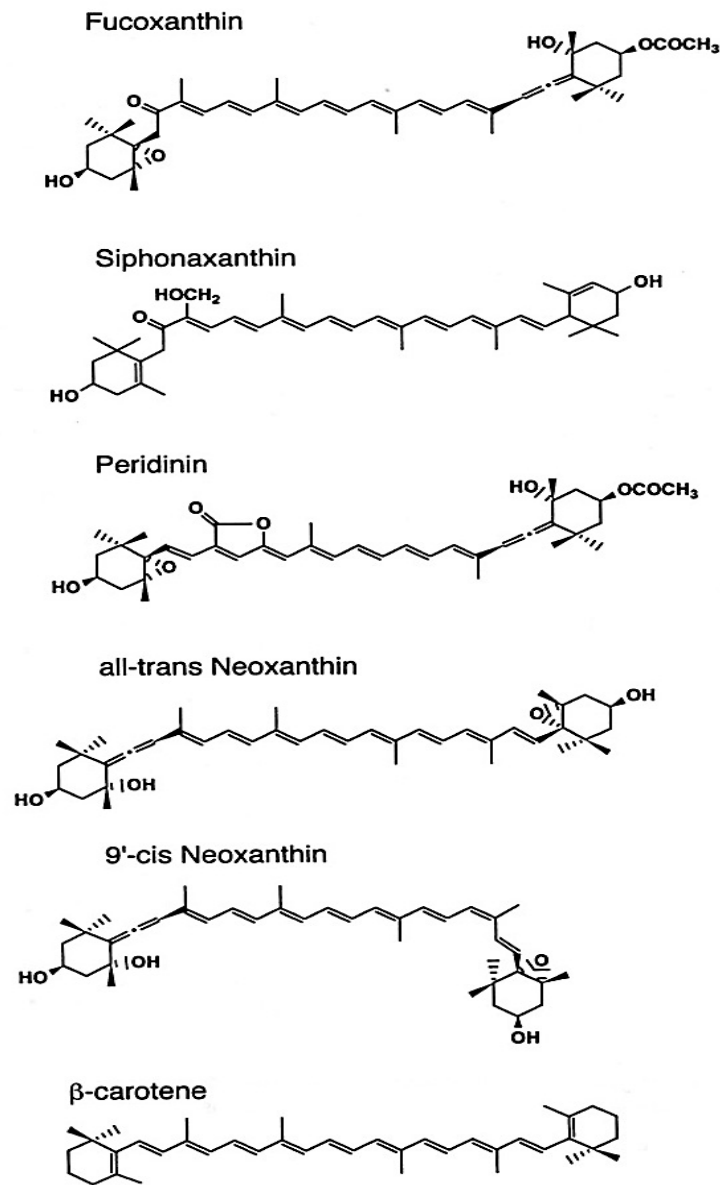


Fig. 2. Molecular structures of several carotenoids characteristic to algae.

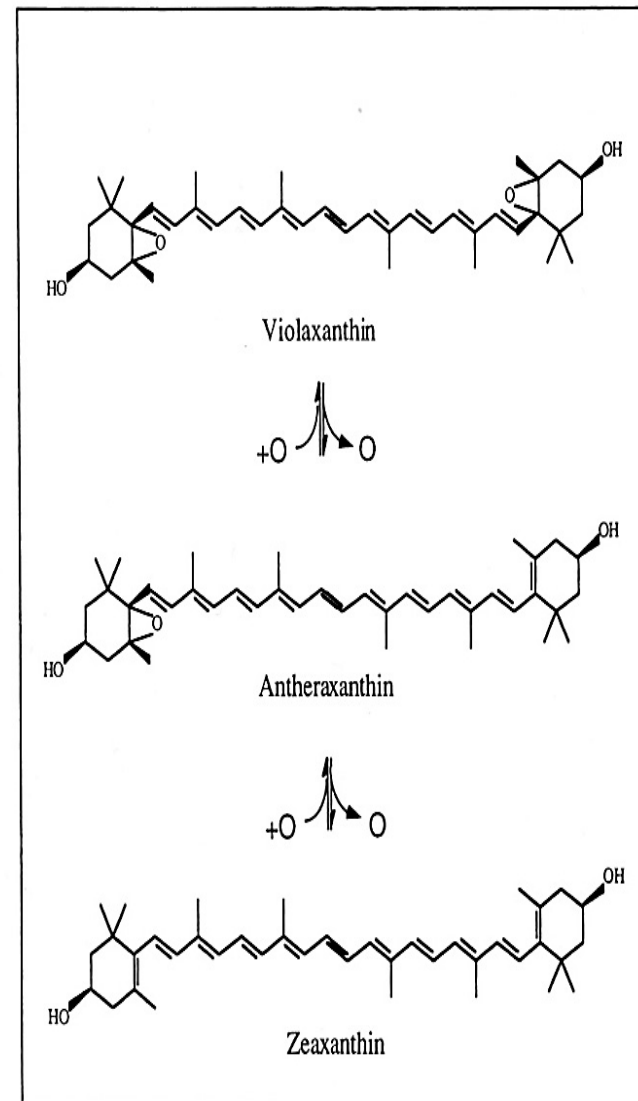
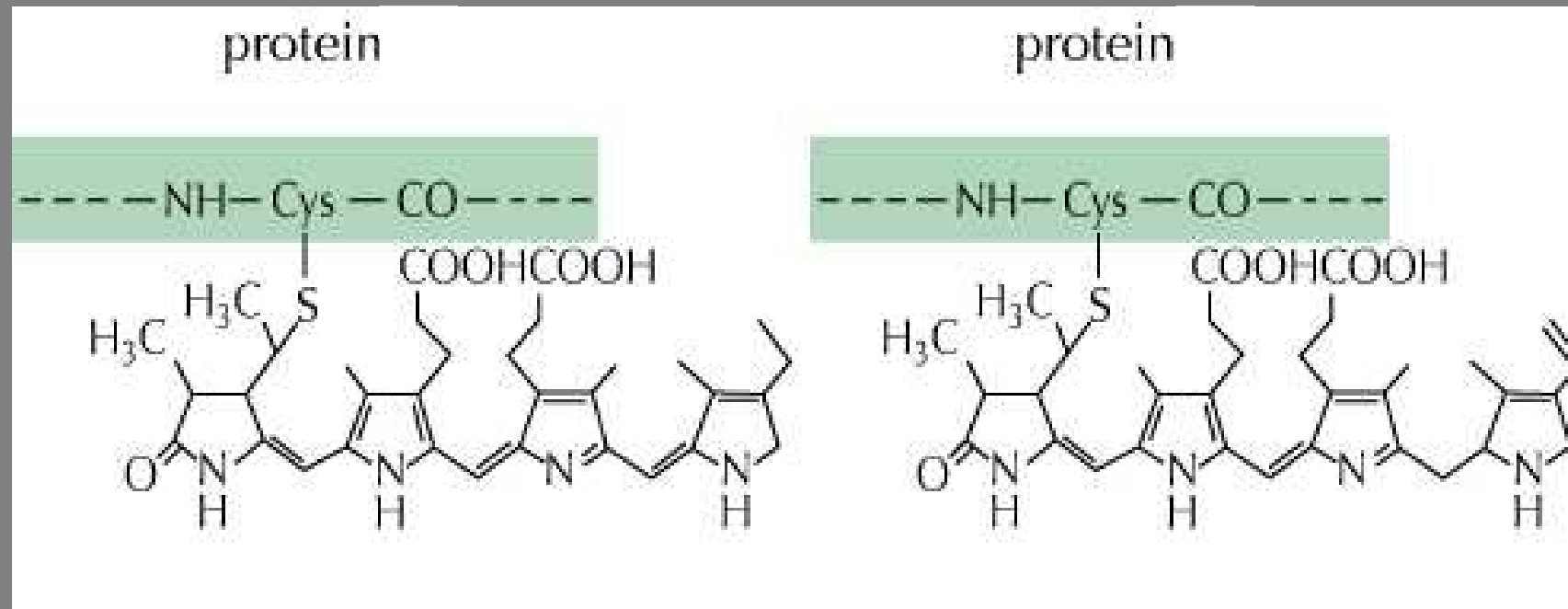


Fig. 3. The key xanthophylls which take part in the xanthophyll cycle of green algae and land plants. In chromophyte algae these xanthophylls are replaced by diatoxanthin and diadinoxanthin which take part in a similar cycle (see Table 3). The downward pathway (de-epoxidation) occurs in light; the upward pathway (epoxidation) occurs in darkness.

Photosynthetic pigments: Phycobiliproteins



Phycocyanin

Phycoerythrin

Absorbance spectra of extracted pigments

Visible light between 500-650 nm is absorbed by phycobiliproteins PE-PC-APC in sequence to transfer energy to Chl *a*

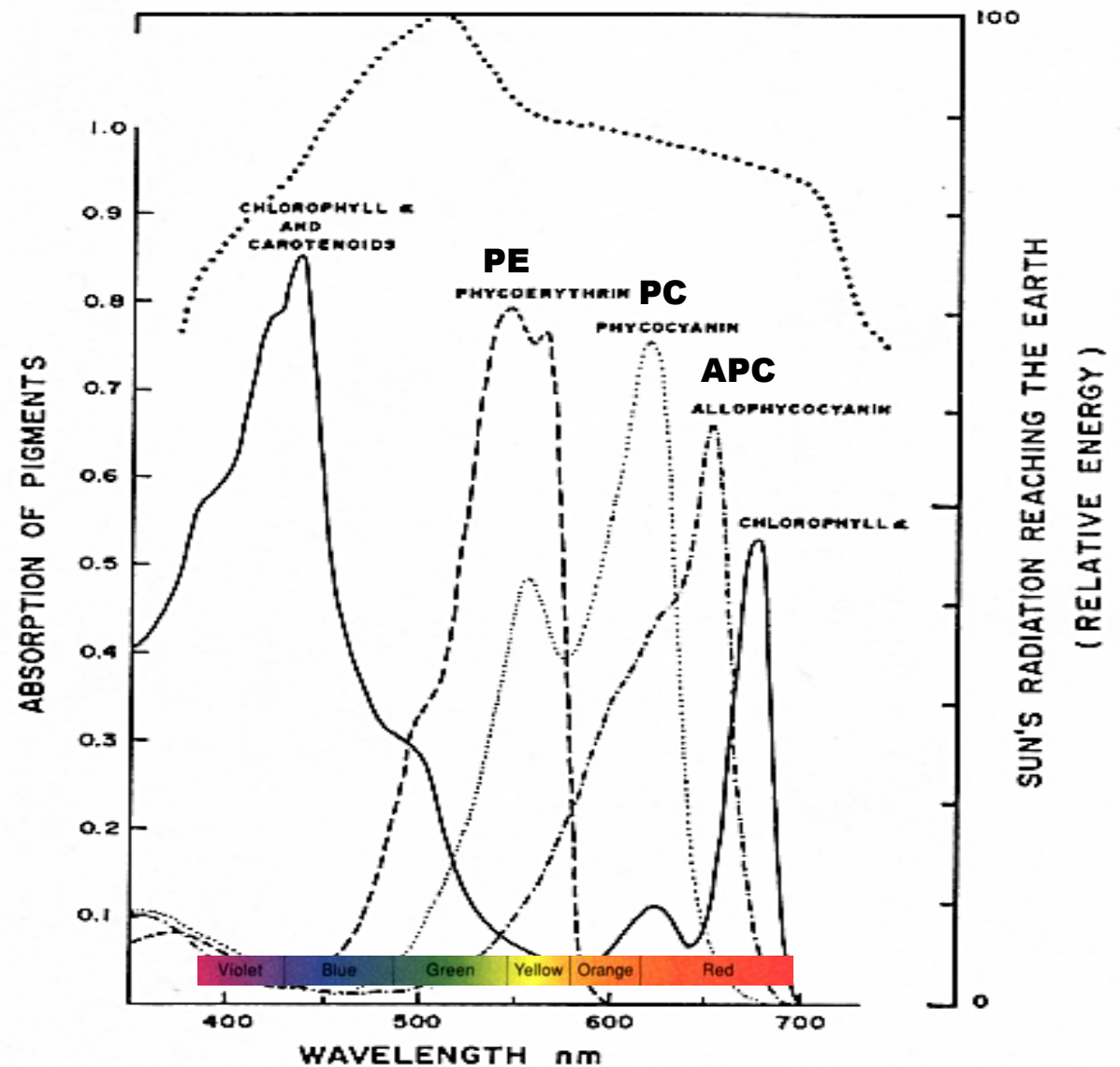


Figure 4.1. Spectrum of solar energy at the earth's surface (upper dotted curve), and absorption spectra of algal pigments.

Photosystem I and II within thylakoids

Phycobilisomes in regular rows on thylakoid surface

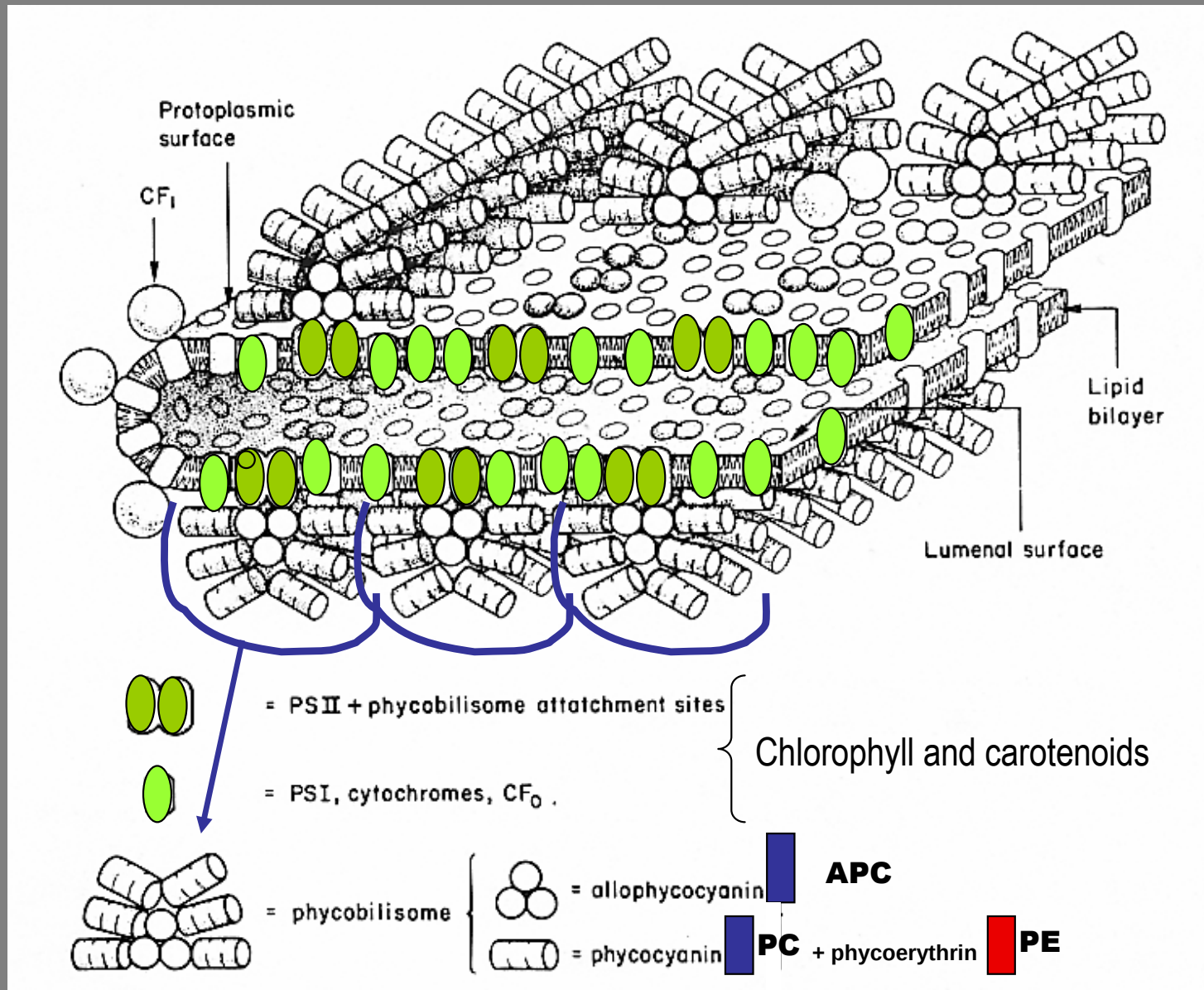


Table 1. Occurrence, distribution, type and spectral characteristics of photosynthetic pigments from cyanobacteria and algae

Pigment	Algal/cyanobacterial group	Chemical type	Major forms	Absorption bands (nm)	Fluorescence emission (nm)*
Chlorophyll <i>a</i>	All organisms	Tetrapyrrol ring, phytol tail	Chl <i>a</i> (minor form Chl <i>a'</i>)	430, 670–690	680 (RT) 680–730 (LT)
Chlorophyll <i>b</i>	Prochlorophytes Green algae Chlorarachniophytes Euglenophytes	Tetrapyrrol ring, phytol tail	Chl <i>b</i> (minor form Chl <i>b'</i>)	455, 650–660	660–670
Chlorophyll <i>c</i>	Chromophytes (except eustigmatophytes)	Tetrapyrrol ring, generally no phytol tail	Chl <i>c</i> ₁ Chl <i>c</i> ₂ Chl <i>c</i> ₃	442–444, 630	633 (640 LT) 635
Chlorophyll <i>d</i>	<i>Acaryochloris marina</i>	Tetrapyrrol ring, phytol tail	Only one form known	380, 440, 700–720	720
MgDVP	Prochlorophytes (some) <i>Acaryochloris</i> ? Micromonadophytes	Tetrapyrrol ring	Only one form known	438, 625	634
Phycobili-proteins	Prochlorophytes <i>Acaryochloris</i> Cyanobacteria Reds Cryptophytes Glaucocystophytes	Open chain tetrapyrrol	Allophycocyanin (APC) Phycocyanin (PC) Phycoerythrin (PE)	625–634 (APC) 610–635 (PC) 495–560 (PE)	570–650
Carotenes	All	carotenoid	α , β , γ	420–470	425–490
Xanthophyll	All	carotenoid	Many forms	410–500 (540)	415–505

For more details on the pigments, refer to Scheer, 1990; Glazer, 1999; Rowan, 1990; Chapter 14, Toole and Allnutt. MgDVP, Magnesium-2,4-divinyl pheoporphyrin methyl ester; RT, room temperature; LT, low temperature (77K). *Fluorescence emission from the intact pigment-protein complex



In vivo absorbance spectra of cyanobacterial cells in cultures acclimated at two irradiances

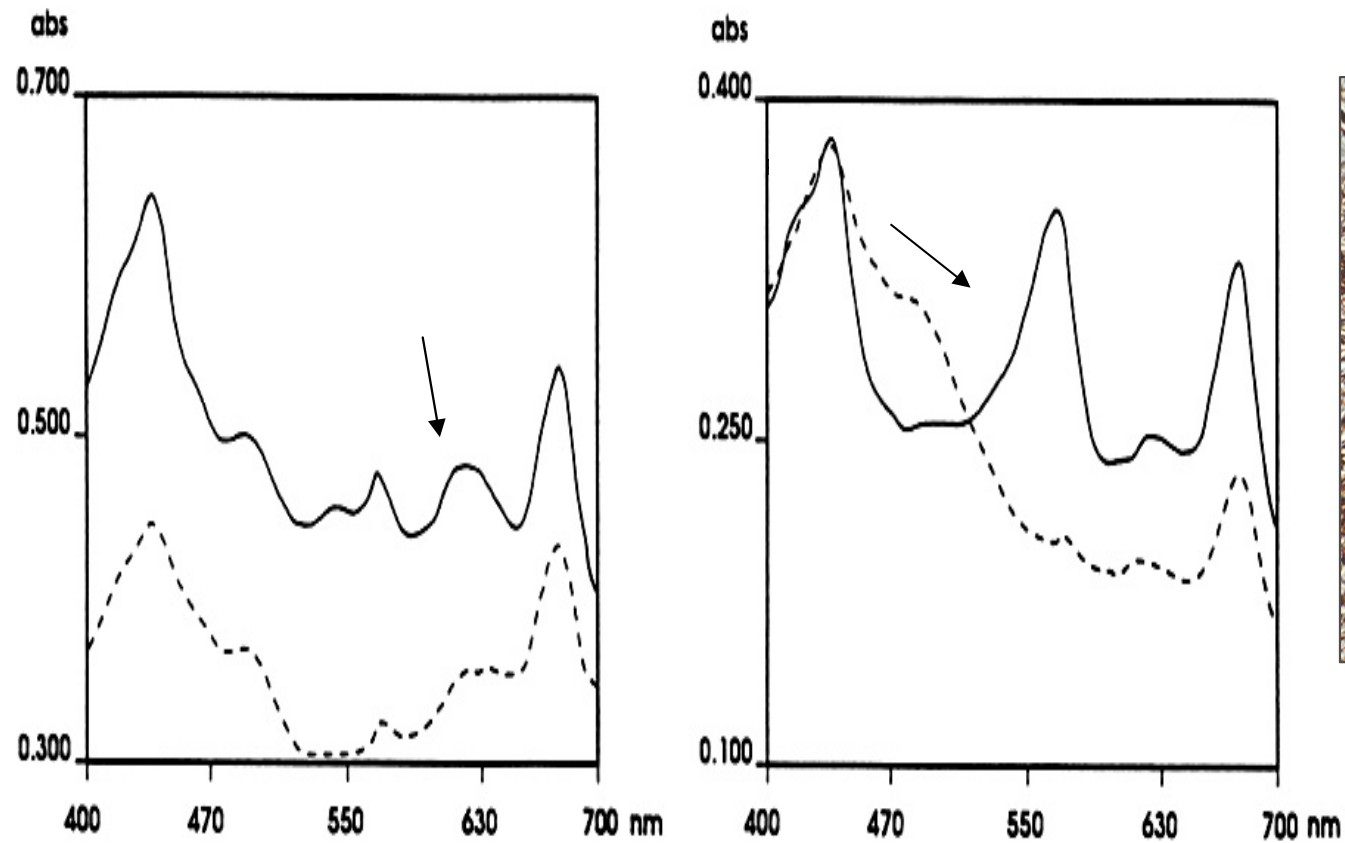
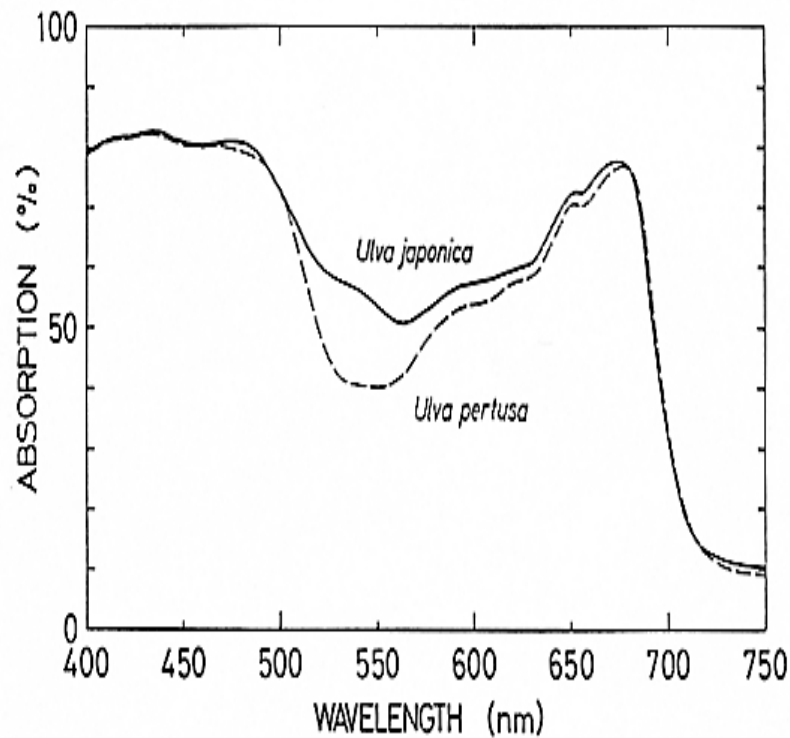


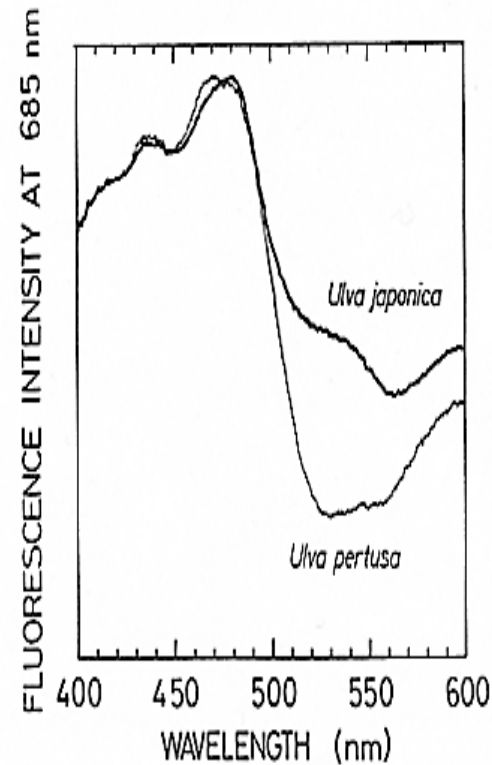
Figure 2. *In vivo* spectra of cyanobacterial cultures grown at two PPFDs: 5 (—) and 60 (-----) $\mu\text{mol m}^{-2} \text{s}^{-1}$. Note differences in the spectra of PC-rich Chroococcalean cyanobacterium (left side), and PE-rich Oscillatorialean cyanobacterium (right side).



Algae living at different depths have different accessory pigments to absorb light



(a)



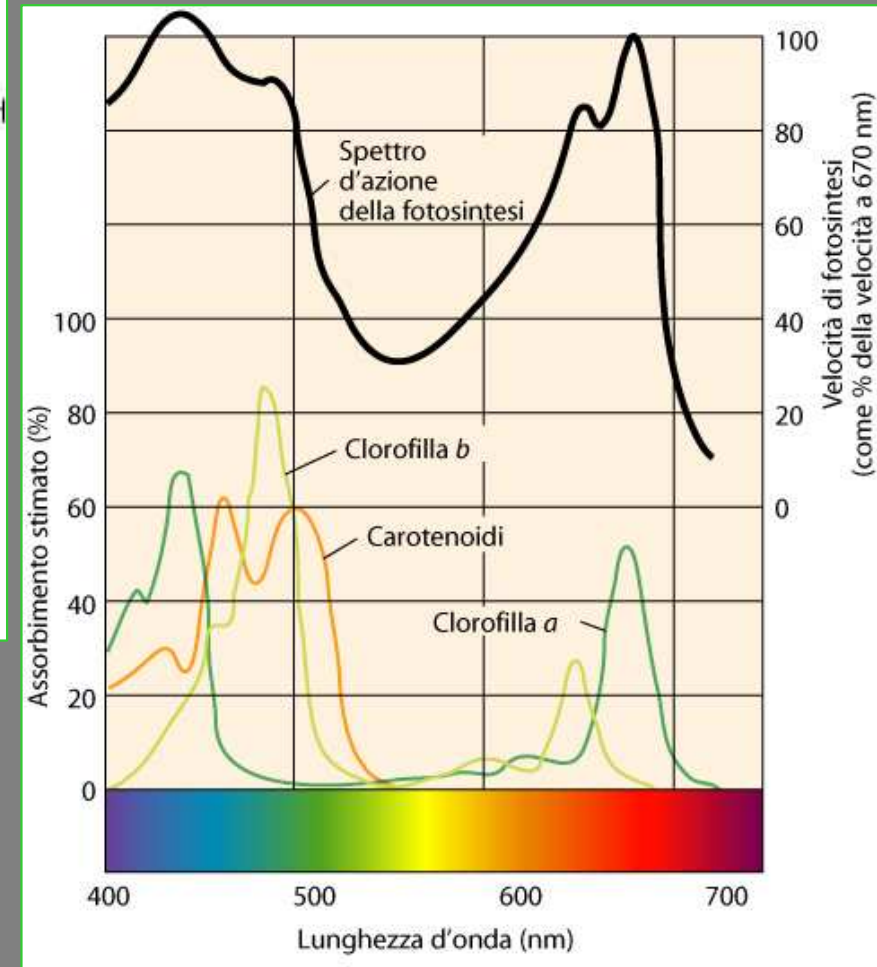
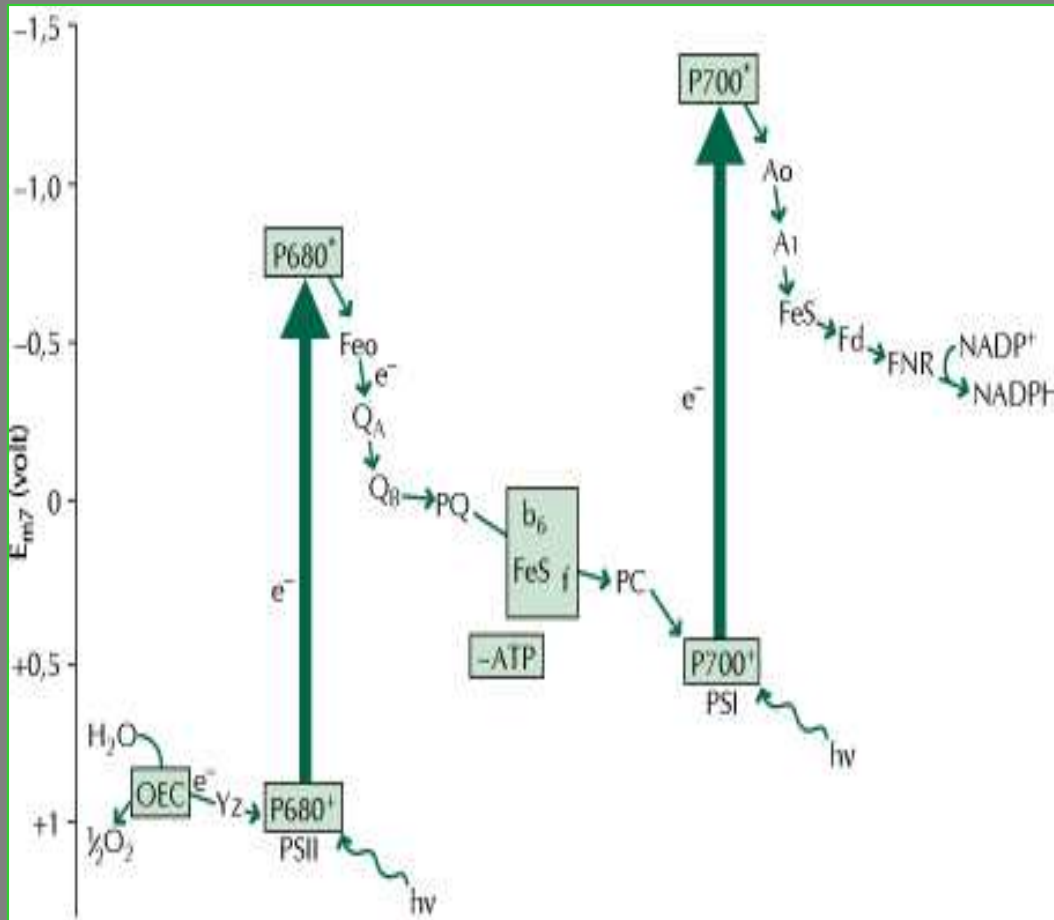
(b)

Figure 4.6. Comparisons of the absorption and fluorescence spectra of *Ulva japonica*, which has siphonaxanthin, and *U. pertusa*, which lacks it. (Lobban & Harrison, 1997)

deep living

shallow water living

Photosynthesis and action spectra



Photosynthesis action spectra vs absorption spectra in living seaweeds

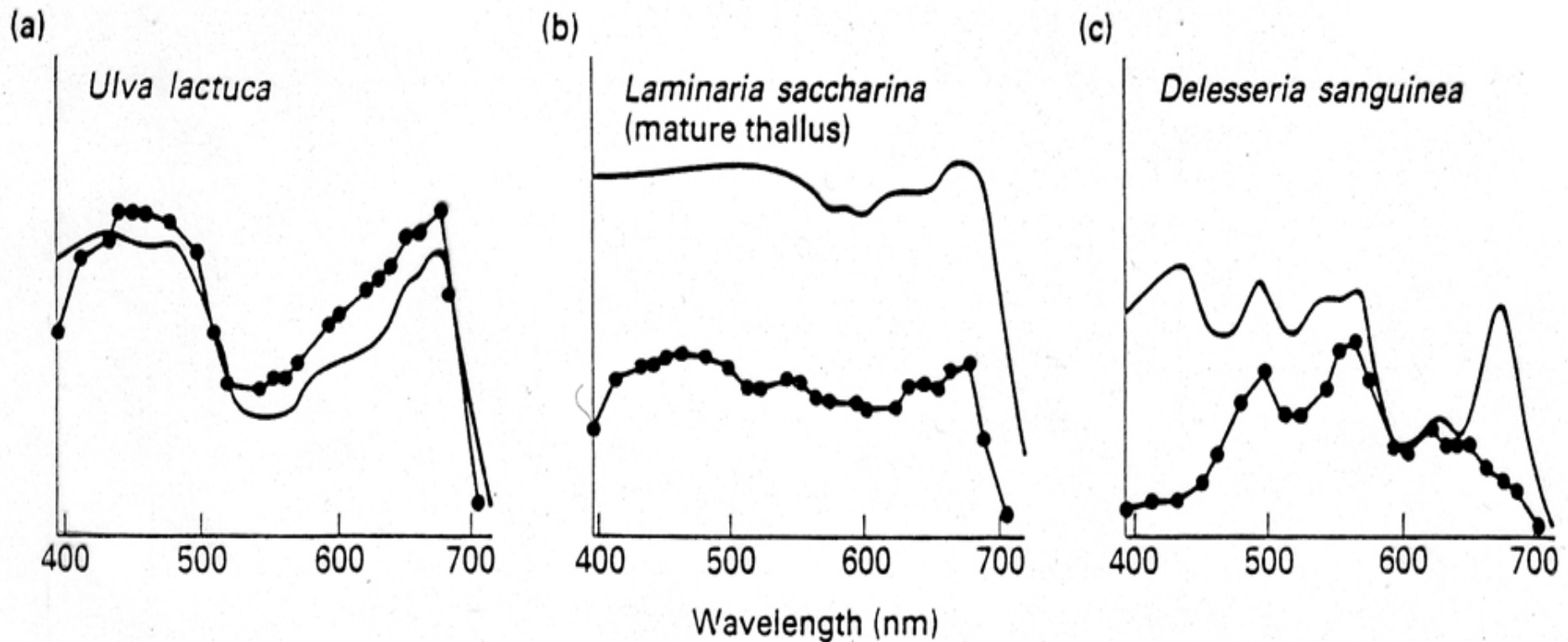
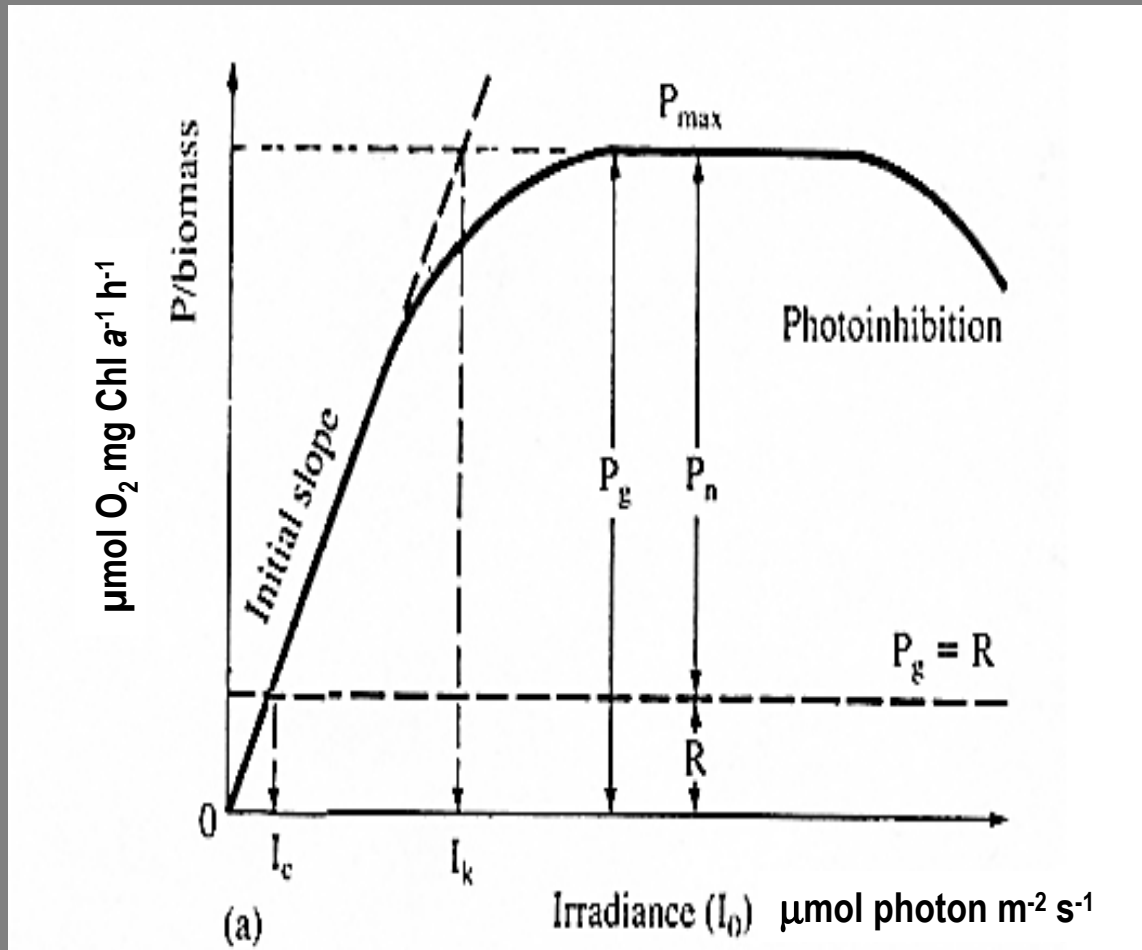


Fig. 6.5 Action spectra for photosynthesis (●) and absorption spectra (—). (a) A chlorophyte *Ulva lactuca*. (b) A chromophyte *Laminaria saccharina* (Phaeophyceae). (c) A rhodophyte *Delesseria sanguinea*. (After Dring, 1982; unpublished data of K. Lüning.)

Photosynthesis *versus* Irradiance (P/I) curves to determine photosynthetic parameters:



I_c – compensating irradiance
($\mu\text{mol photon m}^{-2} \text{ s}^{-1}$)

R - respiration rate
($\mu\text{mol O}_2 \text{ mg Chl } a^{-1} \text{ h}^{-1}$)

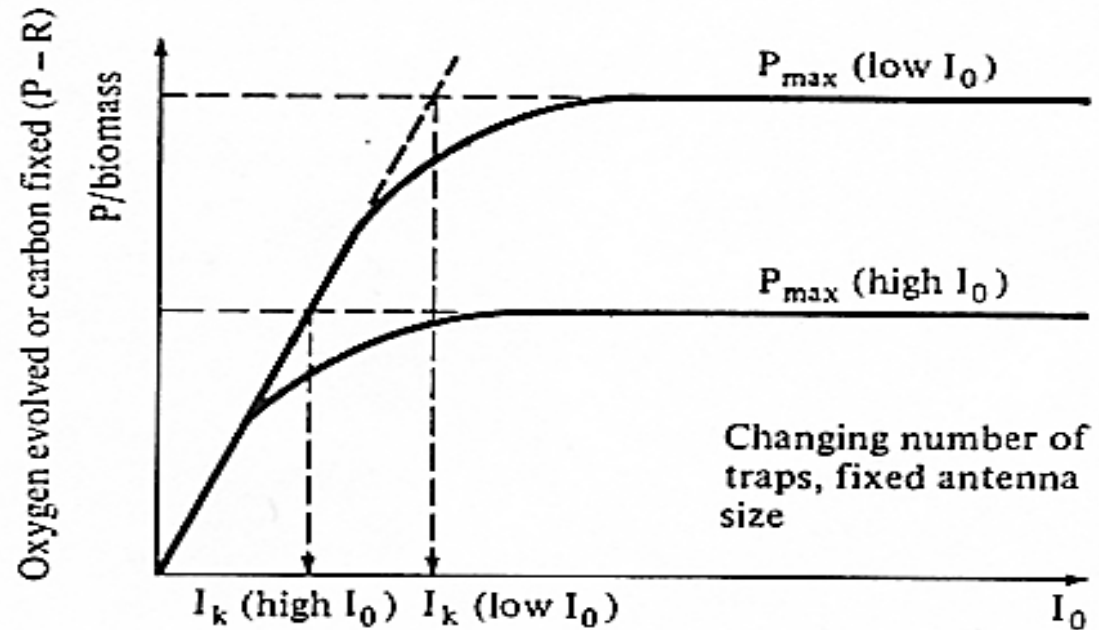
α - photosynthetic efficiency
($\mu\text{mol O}_2 \text{ mg Chl } a^{-1} \text{ h}^{-1} / \mu\text{mol m}^{-2} \text{ s}^{-1}$)

I_k - saturating irradiance
($\mu\text{mol photon m}^{-2} \text{ s}^{-1}$)

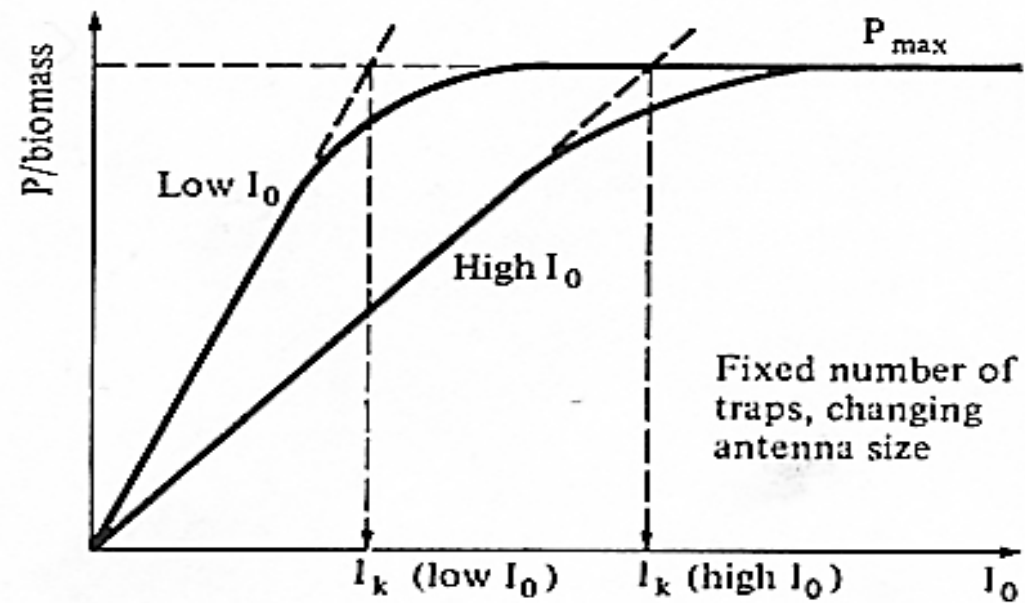
P_{max} - maximum rate of
photosynthesis
($\mu\text{mol O}_2 \text{ mg Chl } a^{-1} \text{ h}^{-1}$)

Acclimation to light:

shade adapted cells
tend to have larger
antennae and lower
compensation points



(b)



(c)