Changes in Light Intensity at Twilight and Estimation of the Biological Photoperiod

By YASUMITSU KISHIDA

Department of Agronomy, Chugoku National Agricultural Experiment Station
(Fukuyama, Hiroshima, 721 Japan)

Introduction

Natural photoperiod is an important environmental factor inducing growth regulation in insects and plants. The natural photoperiod which is used for the analysis of photoperiod is usually based on the possible duration of sunshine (duration from sunrise to sunset). However, it is known that the threshold of light intensity effective for photoperiodism is lower than the light intensity at the time of sunrise or sunset, i.e., it is the light intensity at twilight before sunrise or after sunset. In other words, very low light intensity is effective in inducing photoperiodic response. Therefore, the photoperiod analysis using the natural photoperiod is not sufficient in searching for the biologically effective photoperiod.

The threshold of light intensity which induces photoperiodic response varies depending on the kinds of living organisms, kinds and degree of the response, and conditions. Ordinarily, it ranges from 0.2 to 100 (or 200) lx[1,2,12,14,17]. For example, the threshold for diapause induction is 0.2–1 lx[6] for rice stemborers, 0.1 lx for silkworm eggs, 0.1–0.8 lx[7] for early instar larvae of silkworm, and lower than 25 lx for many other organisms[1]. In case of plant photoperiodism, the threshold for flowering inhibition of short day plants is 5.5 lx for autumn soybean, 3.1 lx[10] for cocklebur, and 1–100 lx[9,13,16] for rice plants, while that for flowering promotion of long day plants is 1–3 lx[15] for China aster etc.

Since the light intensity at the time of sunrise and sunset is 430–670 lx in fine days, and 100–250 lx in cloudy days[4,5], it is apparent that the twilight is contributing appreciably to the photo periodism of living organisms in agricultural systems. In the present paper, changes of light intensity in twilight hours, as influenced by a solar dip and weather, and the method of calculating length of the photoperiod with the light intensity higher than a given arbitrary light intensity are reported.

Method of observation

During the twilight period in the evening, the observation of horizontal light intensity*, the cloud amount, cloud form, and weather phenomena was carried out. The luxmeter used was a photovoltaic cell type TOSHIBA SPI-7. The cloud amount was expressed in ranks from 0/10 to 10/10 by visual observation. The solar altitude at the time of the observation was given by calculation. The observation was carried out during the period from January to March 1985 at the Kyushu National Agricultural Experiment Station (33°12′N, 130°30′E), and from September to October 1986 at the Chugoku National Agricultural Experiment Station (34°30′N, 133°23′E). To avoid the effect of street-lamps, the observation was conducted on the roof of a building.

* Light intensity on the fully exposed horizontal surface. The word, light intensity, signifies it in this paper.

Light intensity at twilight, solar-altitude, and weather

The light intensity at twilight, which changes with solar altitude, is influenced by weather conditions. The result obtained by the observation is shown in a semilogarithmic graph of Fig. 1. The abscissa shows the altitude of the center of the sun, and its negative value indicates inclination below the horizon. The altitude of the center of the

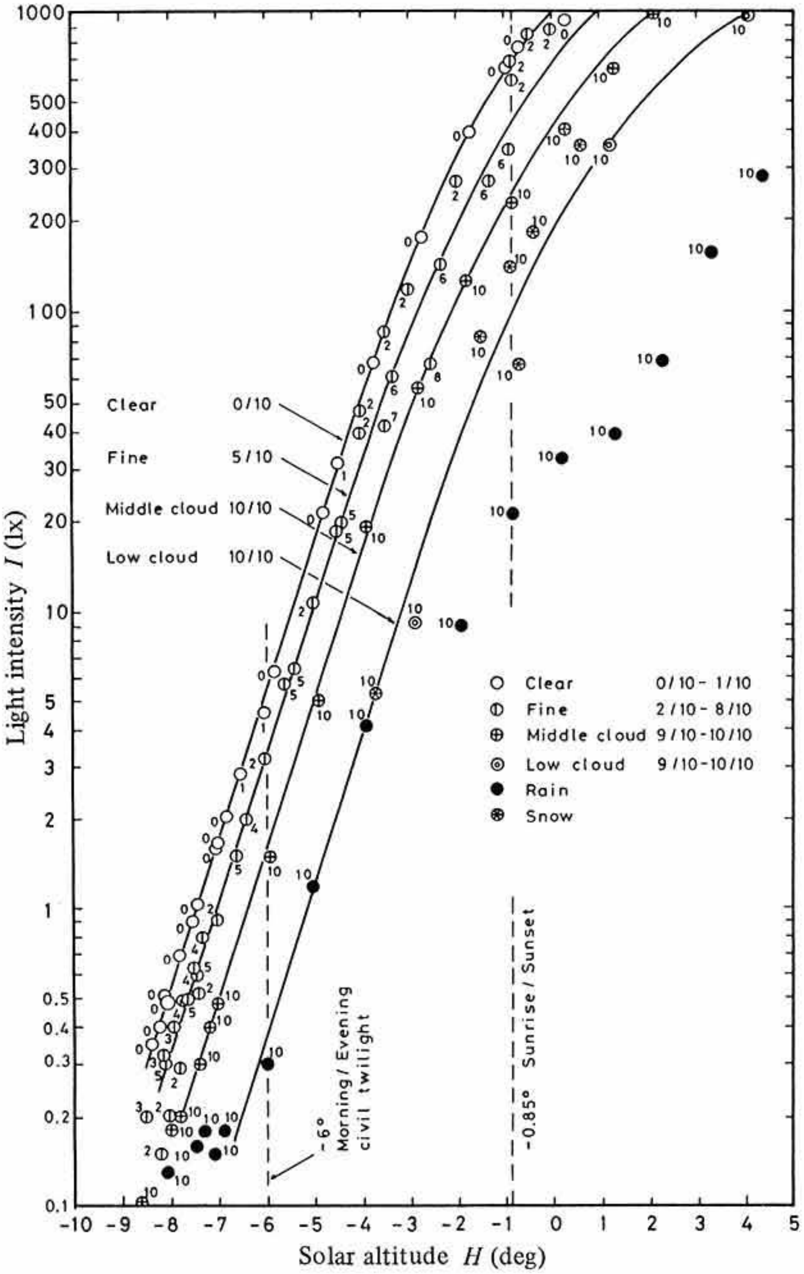

Fig 1. Light intensity at twilight as the function of solar altitude

sun was -0.85 deg at the time of sunrise and sunset, and was -6.00 deg at the start of morning civil twilight and the end of evening civil twilight. The ordinate indicates horizontal light intensity (in lx). In Fig. 1, isolines for clear (cloud amount: 0/10), fine (c.a.: 5/10), and overcast sky (middle c.a.: 10/10 and low c.a.: 10/10) are illustrated.

The relationship between solar altitude (H: deg) and light intensity (I: lx) in the semi-logarithmic graph is nearly linear when I is lower than 50 lx and the cloud amount is unchanged. This relationship is expressed by the following equations[4,5]:

$$H=\alpha \ln I+\beta, \quad \text{.............................(1)}$$

$$\text{or} \quad I=\exp\{(H-\beta)/\alpha\}, \quad \text{....................(2)}$$

where α is a constant, 0.87, irrespective of the cloud amount. The value of β varies with the cloud amount, and is -7.43 for clear, -7.03 for fine, -6.40 for overcast (middle cloud) and -5.15 for overcast (low cloud) sky. These equations can be applied to the range of 0.2–50 lx, which concerns photoperiodism. Besides that range, solar altitude and light intensity observed are shown in Table 1.

In most cases, the threshold of light intensity is 1–5 lx. The solar altitude for that threshold value is -7.4 to -5.0 deg except foul weather. Namely, the solar altitude for 1 lx is -7.4 deg under clear sky and -6.4 deg under overcast (middle cloud) sky. The solar altitude for 5 lx is -6.0 (clear sky) and -5.0 deg (overcast sky with middle cloud). Accordingly, for the biological photoperiod with the threshold of 1–5 lx, data of the photoperiod including the duration of civil twilight should be adopted in place of the natural photoperiod.

In Table 1, results of other researchers[3,11] are also shown. The light intensity at twilight measured in the present study is slightly higher than that so far reported in case of

Table 1. Light intensity at twilight observed by the present author and other researchers under various weather conditions

Solar altitude (deg)	Kishida (1985)				Sharonov (1945)		Kimball (1916)
	Clear* 0/10	Fine 5/10	Middle cloud 10/10	Low cloud 10/10	Clear sky	Low cloud	Clear sky
0	980 lx	680 lx	420 lx	190 lx	651 lx	244 lx	lx
−0.5	800	520	305	135	541	131	
−0.85	670	430	250	103			
−1	620	385	230	90	395	75	323
−1.5	460	280	155	58	285	70	
−2	330	200	110	36	203	28	162
−2.5	220	136	72	21.0	139	15	
−3	145	88	46	11.8	96	9	79.6
−3.5	86	56	28.0	6.7	59	7	
−4	51.6	32.6	15.8	3.8	31	5	33.4
−4.5	29.0	18.3	8.9	2.1	18	3	
−5	16.3	10.3	5.0	1.19	11	2	11.8
−5.5	9.2	5.8	2.8	0.67	6	0.8	
−6	5.2	3.3	1.58	0.38	3	0.5	4.31
−6.5	2.9	1.84	0.89	0.21	2	0.2	
−7	1.64	1.04	0.50	0.12	1	0.1	1.08
−7.5	0.92	0.58	0.28				
−8	0.52	0.33	0.16				0.43
−8.5	0.29	0.18					0.22
−9	0.16						0.16

* Weather conditions (clear, fine, middle cloud and low cloud) are expressed by the amount of clouds in terms of 0/10 to 10/10.

clear sky, but in full accord with that so far reported in case of overcast (low cloud). The present study furnished the detailed data for each of the various amounts of cloud, measured under the condition of relatively high transmission coefficient of the atmosphere.

The distance (radius vector) between the earth and the sun ranges from 0.9832 (in winter) to 1.0167 (in summer)[8]. The radius vector during the observation period of the present study averaged 0.9880. Assuming that the light intensity is inversely proportional to radius vector squared, the seasonal variation of the light intensity determined by the present study is considered within the range of 1% increase in winter and 5% decrease in summer.

Light intensity changes and time passage

In the foregoing section, the relation between light intensity at twilight and solar altitude was made clear. On the basis of this principle, the relation between light intensity and the time of a day can be obtained by using the relation between change of solar altitude and time passage.

In equation (1), by taking $H=H_1$, $I=I_1$, and $\beta=\beta_1$ at the time T_1 and $H=H_2$, $I=I_2$, and $\beta=\beta_2$ at the time T_2, the following equations can be obtained:

$$H_1-H_2=\alpha\{\ln(I_1/I_2)+(\beta_1-\beta_2)\}, \quad \text{.........(3)}$$

$$T_1-T_2=(H_1-H_2)/\Gamma$$
$$=\alpha\{\ln(I_1/I_2)+(\beta_1-\beta_2)\}/\Gamma, \quad \text{......(4)}$$

where Γ is the average changing ratio of solar altitude.

Next, by taking $I_1=I_c$ when $T_1=0$, $I_2=I$ when $T_2=t$, and $\beta_1=\beta_2$ the following equations are obtained:

$$t=(\alpha/\Gamma)\ln(I/I_c), \quad \text{..........................(5)}$$

$$I=I_c\exp\{(\Gamma/\alpha)t\}. \quad \text{..........................(6)}$$

In equations (5) and (6), $\alpha=0.87$. The value of changing ratio, Γ (deg/min) was calculated for the range of solar altitude from −8 deg to −4 deg, for different latitudes and seasons, and shown in Table 2.

Now, I_c is the light intensity at the time T_1. If T_1 is taken as the start of morning or the end of evening civil twilight (at −6 deg of solar altitude), I_c is 5.2 lx (clear), 3.3 lx (fine) and 1.58 and 0.38 lx (overcast sky), and t is the time (min) elapsed from T_1. The value of I_c in equations (5) and (6) is not determined by the cloud amount at the time T_1, but should be determined by the cloud amount t min after T_1.

As a simple example, the time (τ) which passes for the decrease of light intensity in the evening to a half ($I_2=I_1/2$) is expressed

Table 2. Changing rate of solar altitude with time ($\Delta h/\Delta t$) and half value period (τ) of light intensity during twilight hours below 50 lx

Latitude deg N	Dec. 22		Feb. 4, Nov. 8		Mar. 21, Sep. 23		May 6, Aug. 8		Jun. 22	
	$\Delta h/\Delta t$ (deg/min)	τ (min)	$\Delta h/\Delta t$ (deg/min)	τ (min)	$\Delta h/\Delta t$ (deg/min)	τ (min)	$\Delta h/\Delta t$ (deg/min)	τ (min)	$\Delta h/\Delta t$ (deg/min)	τ (min)
0	0.229	2.63	0.240	2.51	0.250	2.41	0.240	2.51	0.229	2.63
5	0.229	2.63	0.240	2.52	0.249	2.42	0.238	2.53	0.227	2.66
10	0.227	2.66	0.237	2.54	0.246	2.45	0.234	2.57	0.223	2.71
15	0.223	2.71	0.233	2.59	0.241	2.50	0.229	2.64	0.217	2.79
20	0.217	2.78	0.227	2.66	0.235	2.57	0.221	2.73	0.208	2.90
25	0.208	2.89	0.219	2.76	0.226	2.66	0.211	2.86	0.197	3.05
30	0.198	3.04	0.209	2.89	0.216	2.79	0.200	3.02	0.185	3.27
35	0.186	3.24	0.197	3.06	0.204	2.95	0.186	3.24	0.169	3.56
40	0.173	3.49	0.184	3.28	0.191	3.16	0.170	3.54	0.152	3.98
45	0.157	3.85	0.169	3.57	0.176	3.43	0.153	3.95	0.131	4.61
50	0.139	4.33	0.153	3.95	0.159	3.78	0.132	4.55	0.106	5.67

by the following equation, when the cloud amount is unchanged ($\beta_1=\beta_2$):

$$\tau=0.603/\Gamma. \quad \text{(7)}$$

The half value period of light intensity in the evening is equal to the doubling period of light intensity in early morning. The value of τ is given in Table 2. At the same latitude, it is short at the vernal equinox and the autumnal equinox, and long at the summer solstice, but such a seasonal change is small at low latitude.

Examples of actual calculation

On the basis of the foregoing knowledge, examples of calculation of the photoperiod with a given threshold light intensity will be shown below. The calculation is valid for the range of light intensity lower than 50 lx, and the time of sunrise and sunset, and the duration of civil twilight have to be known in advance.

At the site of 25°N, 125°E (in the sea near Okinawa), the sunrise and sunset time is 7:21 and 17:56 (J.S.T.), and the duration of civil twilight is 25 min before sunrise and also after sunset at the winter solstice, according to Smithonian Meteorological Tables[8] etc. Accordingly, morning civil twilight begins at 6:56 and evening civil twilight ends at 17:31, and I_c at each time is 5.2 lx (clear), 3.3 lx (fine), 1.58 lx (overcast: middle cloud), and 0.38 lx (overcast: low cloud), according to Table 1.

Example 1: How to know the time when I becomes 0.3 lx: In equation (5), α is always 0.87, and Γ is 0.208 deg/min (Table 2). Under the clear sky, the time (t) elapsed for the change of light intensity from 5.2 lx to 0.3 lx is calculated as follows:

$$t=(0.87/0.208)\ln(0.3/5.2)=-12 \text{ min}.$$

Namely, the light intensity becomes 0.3 lx at 12 min before the start (6:56) of morning civil twilight and after the end (17:31) of evening civil twilight, i.e., at 6:44 and 17:43, respetivcely. The photoperiod with light intensity higher than 0.3 lx is 10 hr 59 min.

Example 2: How to know the light intensity after 10 min from the start of morning civil twilight or from the end of evening civil twilight: In equation (6), $I_c=3.3$ lx when the weather at the time 10 min after is fine. The light intensity at 10 min after the beginning (6:56) of morning civil twilight is calculated as follows:

$$I=3.3\exp\{(0.208/0.87)\times 10\}$$
$$=36 \text{ lx at } 7:06.$$

The light intensity 10 min after the end (17:31) of evening civil twilight is obtained as follows:

$$I=3.3\exp\{(0.208/0.87)\times(-10)\}$$
$$=0.3 \text{ lx at } 17:41.$$

Example 3: To know approximate changes in light intensity with time, it is convenient to use the half value period (τ in Table 2) of light intensity, when the cloud amount is unchanged. At the winter solstice at 25°N, $\tau=2.89$ min (2 min 53 sec). For example, light intensity of 30 lx in the evening decreases by every 3 min (approx.) to 15, 7.5, 3.8, 1.9 and to 0.91 lx. Therefore, after about 15 min (precisely, 14.2 min according to equation (4)), the light intensity becomes 1 lx. As mentioned already, this half value period is equal to the doubling period in the early morning. Therefore, the difference between the photoperiod with light intensity higher than 30 lx and that with light intensity higher than 1 lx is shown to be 28.4 min.

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