Measurement of Light Environment with a Chemical Radiation Meter Using Anthracene-Ethyl Alcohol Solution

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Abstract

The anthracene method which is one of the techniques for assessing the light environment in ecological studies, is described with a view to utilizing in for practical applications. This method is based on the photochemical reaction of anthracene in an alcohol solution. The advantages of the method are that the light environment can be measured in many positions at the same time regardless of the weather conditions. The disadvantages are that the method tends to be time-consuming for the derivation of basic regression equations and the procedures preceding and following the field measurements, and that the chemical reaction is related to ultraviolet radiation, although the regression is usually derived based on the calculation of the photon flux density, illuminance or total irradiance. These characteristics are described along with the theory of the method. Practical procedures for laboratory and field measurements are described with some examples on the estimation of relative radiation in forests.

Discipline: Forestry and forest products
Additional key words: anthracene method, relative radiation

Introduction

Light measurement is important for the analysis of the structure and function of forests and other plant communities. Although photosensors are generally used, measurements of instantaneous light flux values fluctuate considerably in a forest, due to the presence of sunflecks under sunny skies. To alleviate this shortcoming a large number of photosensors could be used simultaneously to compensate for the large variations in the light values. This approach is, however, often unpractical for economic reasons. Therefore in practice, the use of photosensors is limited to cloudy days for the measurement of steady-state relative light flux density. This limitation may lead to the collection of an insufficient number of data when working under a tight schedule. We describe here a simple method using a chemical radiation meter that utilizes anthracene. It has some advantages that cannot be met by the conventional methods of light

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measurement with photosensors.

The chemical radiation meter described here measures the radiation based on the photochemical reaction of anthracene ($C_{14}H_{10}$), which is soluble in organic solvents such as alcohol or benzene. Upon the exposure to solar radiation (ultraviolet radiation), anthracene in the solution polymerizes into insoluble dianthracene (($C_{14}H_{10})_2$). Thus the radiation amount can be calculated by measuring the concentration of anthracene before and after the exposure. This technique is hereafter referred to as the anthracene method.

The anthracene method which was first introduced by Dore[2], was applied to measurements in forests and to the evaluation of herbicide tests[8,9,13]. Benzene was used as a solvent. Thereafter, radiation measurements were performed in forests using an anthracene–ethyl alcohol solution[1,4-6,12] due to the ease of handling. Detailed examinations were carried out to obtain more accurate measurements[3,11]. Here we describe a chemical radiation meter using the anthracene–ethyl alcohol solution proposed by Hagihara et al.[3,4], in relation to applications to forest ecological studies.

Theory and characteristics of the anthracene method

1) Principle of the method

Anthracene–ethyl alcohol solution shows an absorption spectrum with peaks in the 250–400 nm range. The relationship between the absorbance D and concentration of anthracene C (mg/l) is expressed by the function:

$$D = kC, \quad (1)$$

where k is a coefficient. The values of k at some wavelengths with higher peaks of absorption, using a quartz cell 10 mm wide, are 4.407×10^{-2} l/mg at 356.8 nm, 4.219×10^{-2} at 375.9 nm and 2.149×10^{-2} l/mg at 350 nm[3].

Anthracene in ethyl alcohol polymerizes into insoluble dianthracene upon exposure to solar radiation. The relationship between the concentration of anthracene C and the integrated radiation I is expressed as:

$$C = A\exp(-\mu I), \quad (2)$$

where A is the initial concentration of anthracene and μ is a coefficient. Equation (2) can be applied when I is represented in terms of integrated photon flux density (PFD) in E/m^2, integrated illuminance in klx·h or integrated total irradiance in W·h/m^2[11]. Fig. 1 shows some examples of the validity of Eq.(2). The figure indicates two important characteristics: (1) linearity on the semilog coordinates can be applied within the range of I or below the upper limit of I. The upper limit decreases for a higher initial concentration A; (2) the constant μ also varies with A. From Eq.(2), the relative radiation inside a canopy, I'/I_0 is calculated as:

$$I'/I_0 = \frac{\ln A - \ln C_i}{\ln A - \ln C_0}, \quad (3)$$

where I' and I_0 are the radiation measurements inside and outside the canopy. C_i and C_0 are the concentrations of anthracene upon exposure inside and outside the canopy. From Eq.(1), the relative radiation is also expressed as:

$$I'/I_0 = \frac{\ln D_A - \ln D_i}{\ln D_A - \ln D_0}, \quad (4)$$

where D_A is the absorbance of the initial solution, and D_i and D_0 are the absorbances upon exposure inside and outside the canopy, respectively.

2) Characteristics of the anthracene method

The advantages of the anthracene method are as follows: (1) light environment can be measured at many points at the same time and in any places; (2) the relative radiation can be measured regardless of the weather conditions; (3) light environment is evaluated in terms of
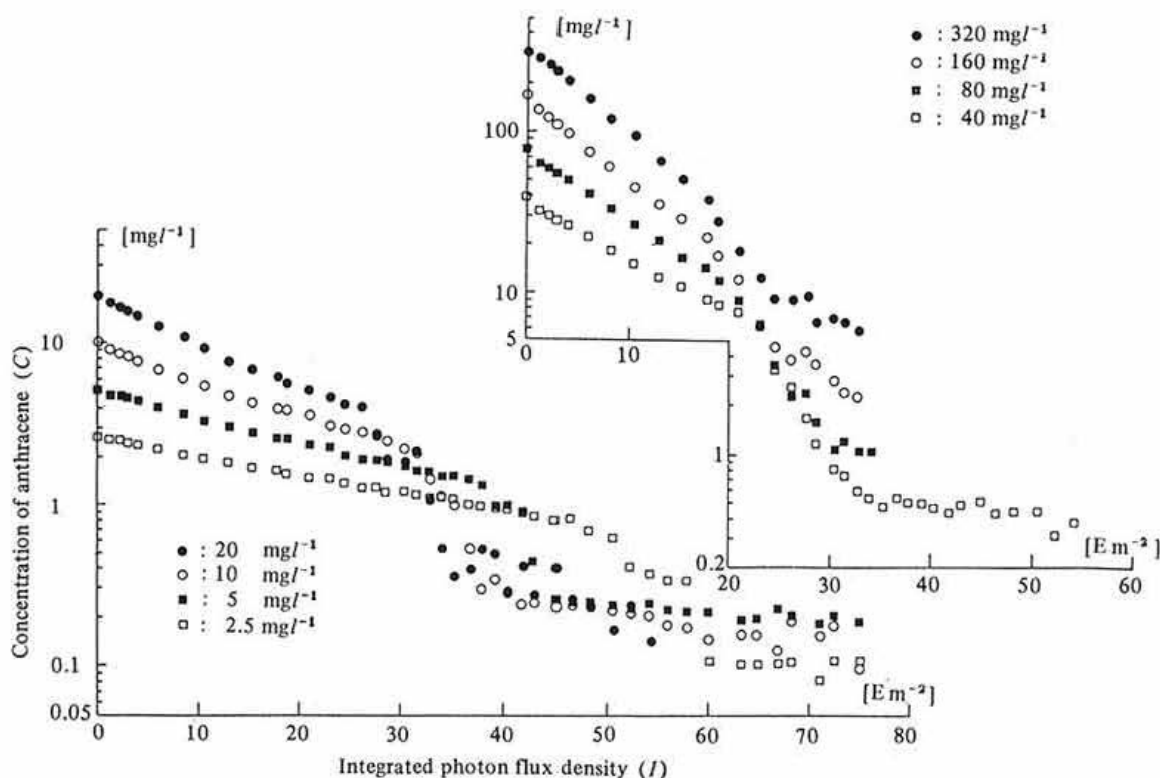
Fig. 1.   Relationship between the concentration of anthracene in the solution (C) and
the integrated photon flux density (I)[3]
The experiment was conducted using vials with caps upward.

an integrated parameter. On the other hand,
the disadvantages of the method are as follows:
(1) the procedures for the application of the
method before and after field work are time-
consuming; (2) the reaction of anthracene is
related to ultraviolet radiation and not to the
total radiation or photosynthetically active radi-
ation, although the regressions are obtained
based on PFD, illuminance or total irradiance;
(3) the light environment is evaluated only at
the integrated level.

Application of the anthracene method

The procedures for the preparation of the
anthracene–ethyl alcohol solution and for the
field measurements are as follows. It must be
emphasized that since a large quantity of alco-

hol is used in the whole process, care must be
taken to avoid fire. Also anthracene may cause
skin irritation[9].

1)   Determination of concentration

The maximum amount of radiation measura-
ble with this method is smaller when the con-
centration of the anthracene solution is higher.
Table 1 lists approximate maximum values of
integrated PFD and lower limits of concentra-
tion based on Fig. 1. On the other hand, the
value of μ is larger when the concentration of
the solution is higher, suggesting that the sen-
sitivity is higher when the concentration of the
solution is higher. Thus the anthracene con-
centration must be determined based on the
amount of solar radiation in the seasons and
the location of the measurement. Table 1 can

Table 1. Approximated figures of the maximum integrated photon flux density measured by using the solution and corresponding concentration of residual anthracene

Initial concentration (mg/l)	Maximum integrated PFD (E/m^2)	Concentration of residual anthracene (mg/l)
320	20	20
160	20	10
80	22	7
40	22	7
20	25	4
10	30	2
5	38	1.5
2.5	52	0.6

The values were cited from Fig. 1. The experiment was conducted using vials with caps upward.

be used to estimate the approximate concentration of anthracene under various conditions.

The concentration is estimated by measuring the absorbance with a spectrophotometer. Wavelength of the measurement should be determined by considering the appropriate range of measurements of the instrument.

2) Preparation of anthracene–ethyl alcohol solution

Materials and instruments are as follows: anthracene; ethyl alcohol (99%) required for both the solution and other preparation procedures; a bottle (large enough to make the solution); a magnetic stirrer; a balance (precision: 1 mg); a spectrophotometer and a set of cells for ultraviolet radiation; pipettes.

The total amount of the solution to be prepared depends on the volume and the number of vials that will be used in the field experiment. The loss associated with the determination of the concentration and vial-filling should also be considered. The numbers of vials should include those for the control (without exposure) and for the measurement of I_0. A number of vials amounting to 5 to 10% of the total number of vials is suitable for the control.

The required amount of anthracene (a solid substance) is roughly weighed with a balance. Anthracene is dissolved in alcohol in a bottle placed under dark conditions by mixing with the magnetic stirrer for about one day. The bottle must be wrapped to avoid evaporation of alcohol. After complete dissolution of anthracene, the concentration of the solution is checked by measuring the absorbance.

3) Filling vials with the solution

Instruments: Vials (the type used in the following experiment is the 4 ml screw vial S–1, Nichiden-rika-garasu, 15 mm in diameter and 45 mm in height) with cap packings (polyethylene cap packings are recommended because they are insoluble in ethyl alcohol, airtight and economical); containers (to hold the vials); an autoburet or a dispenser (convenient for preparing a large number of vials).

The vials are filled with the solution. Although the exposure of the solution to room light does not affect appreciably the concentration, it is preferable to keep the exposure to a minimum. The time required for filling and capping should be short to avoid evaporation. When rubber bands or other instruments are used for setting the vials in the field, they should be placed on the vials at this stage. Until exposure in the field, the vials must be stored in lightproof containers or in a dark room. The solution in the vials can be maintained at a constant concentration in the dark for a long period of at least several months.

4) Field measurement

For measuring the relative radiation, the vials containing the anthracene solution are placed in targetted positions in the plant canopy. Vials are also located outside the canopy for determining I_0 (100% relative radiation) and in a lightproof box for control (0% relative radiation). The vials inside and outside the canopy must be set using the same tools and in the same way.

To measure the light environment during a whole day, the vials should be set before sunrise and collected after sunset. When it is impossible to set the vials before sunrise, they can also be set in the daytime and removed on the next day at the same time. When the setting takes a long time or the weather conditions rapidly change during the setting, it is recommended to place several I_0 sets corresponding to the vials that are placed inside the canopy at different times. After retrieving the vials, they must be kept in a lightproof box or in the dark.

5) Measurement of absorbance for each vial

Absorbance is measured after keeping the vials without disturbance for at least about one day to enable dianthracene to settle at the bottom of the vials. The top clear part of the solution in a vial is transferred to a cell, and the absorbance is measured. Relative radiation is calculated by Eq.(4) based on the absorbance of I_0 and the control.

Examples of field measurements

1) Measurement of light conditions for sub-canopy trees in multiple-layered forests

Using the anthracene method, the light conditions of the trees in a lower canopy layer of *Chamaecyparis obtusa* forests were measured for analyzing the relationship between the light conditions and tree growth. The forests were characterized by a multiple-layered canopy structure. In five stands located on the western slope of Mt. Tsukuba, Japan, the relative radiation just above the lower trees and their size were measured. The stand consisted of different stem densities of upper layer trees and an identical density of lower layer trees.

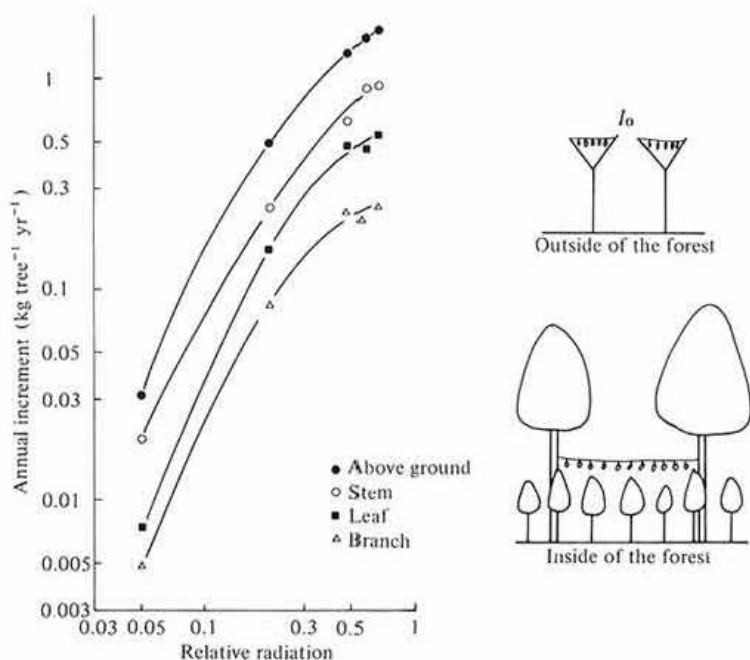The initial concentration of the anthracene-ethyl alcohol solution was about 6 mg/l and

Fig. 2. Relationship between the relative radiation and the mean annual increment of lower layer trees in multiple-layered forests
Schematic drawing shows the setting conditions of the experiment.

the wavelength at which the absorbance was measured was 356.8 nm. The solution was divided into 4 m*l* vials (Nichiden-rika-garasu). In one plot, 60 vials were placed on strings, 1.2 mm in diameter, with rubber bands attached to the vials. The vials were set just above the top of the lower trees at a height in the range of 2.5 – 5 m, utilizing the stems of the upper layer trees (Fig. 2). The vials were placed in the daytime on 4 September, 1992, and were collected on the next day at the same time as the setting. It was cloudy on both days with
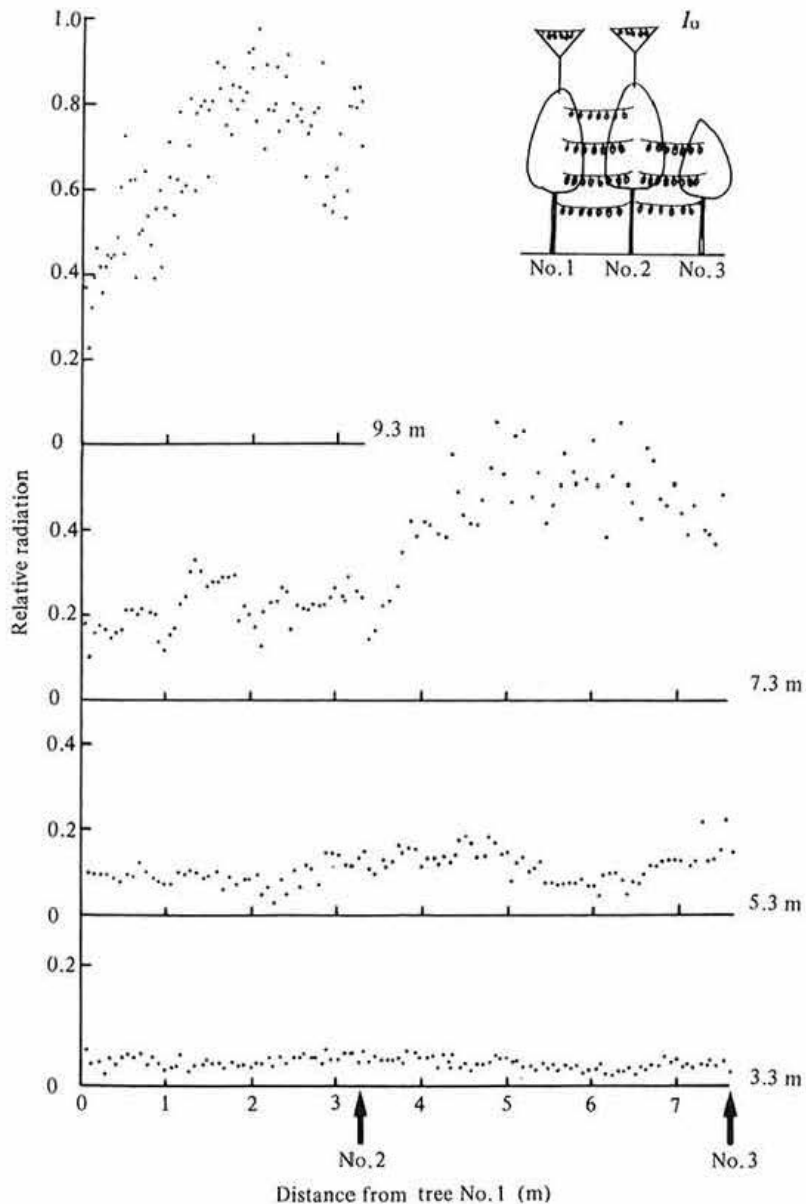

Fig. 3. Vertical and horizontal distribution patterns of the relative radiation in a Japanese larch forest[7]

occasional sunshine. Fig. 2 shows the relation-
ship between the relative radiation and the an-
nual growth rate of each organ of individual
trees, indicating that the annual growth rate
increased with the increase in relative radiation.

2) Vertical radiation distribution in a Japanese larch forest

Vertical patterns of the relative radiation were
observed with the corresponding profile of leaf
biomass density in a 17 years old *Larix kaemp-
feri* plantation[6,7]. The stand density was about
2,500 trees/ha and the mean tree height was
about 10 m. Vials (same type as those used
above), each containing 4 ml solution, were set
among three larch stems at heights between 9.3
and 1.3 m above ground (Fig. 3). Strings and
rubber bands were used for building the ap-
paratus. Sixty vials were placed between two
stems for each height level. Field experiment
was conducted in August. Although the initial
concentration of the solution was as high as
30 mg/l, the extent of the change (reduction)
in concentration (caused by the photochemical
reaction) remained within an acceptable range
of linearity, due to the cloudy condition. The
locations of the vials were recorded when they
were collected. After the vials were removed,
their absorbance was determined using a digi-
tal spectrophotometer at the wavelength of 350
nm. Fig. 3 shows the relative radiation along
the positions within the canopy. Relative radi-
ation was lower near the stems, and higher in
intermediate positions between the stems. Light
extinction coefficient[10] was estimated at 0.46
ha/ha from the cumulative leaf area density
and the vertical distribution of relative
radiation.

Further considerations about the method

One of the potential problems of the anthra-
cene method could arise in the determination
of the concentration. The concentration of an-
thracene is closely related to the maximum radi-

ation that can be measured and to the sensitivity
to solar radiation. First, care must be taken
so that the measurements are performed in the
range below the maximum radiation value. As
a result, under high solar radiation, the con-
centration should be low. However, since a
solution at a low concentration shows a low
sensitivity, small differences in radiation among
positions may not be detectable in darker places
(e.g. forest floor). This problem can be over-
come using two levels of concentration. Two
approaches can be considered.

The relationship between the coefficient μ and
the initial concentration A in Eq.(2) can be ap-
proximated, within the range between $A = 5$
and 40 mg/l, by a power function as[3]:

$$\mu = g \ A^h, \qquad\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots (5)$$

where g and h are coefficients[3]. The value
of h was estimated at 0.423. When the solu-
tion with a low concentration (initial concen-
tration is A_1) is set outside the canopy, and
a solution with a high concentration (initial con-
centration is A_2) is set inside the canopy, the
relative radiation inside the canopy I'/I_0 is
calculated as:

$$I'/I_0 = (A_1/A_2)^h \ \frac{\ln \ (A_2/C_2)}{\ln \ (A_1/C_1)}, \ \cdots\cdots (6)$$

where C_1 and C_2 are the concentrations of
residual anthracene in the solution exposed out-
side and inside the canopy, respectively. It is
preferable to determine the h value under the
experimental conditions, as h is an important
variable for the calculation of the relative radi-
ation from Eq.(6).

The other method is based on the utilization
of the measurements in an intermediate posi-
tion. Vials containing a solution with a low
concentration are set outside the canopy and
in the intermediate position, while vials with
a solution at a high concentration are set in
a dark targetted position and in the same in-
termediate position. Relative radiation I'/I_0
is calculated by the formula:

$$I'/I_0 = (I_M/I_0) \times (I'/I_M) \quad \cdots\cdots\cdots\cdots (7)$$

where I_M/I_0 is the relative value of radiation in the intermediate position to that outside the canopy. Similarly, I'/I_M is the relative value of radiation in the targetted position to that in the intermediate position.

The other problem to address is related to the chemical characteristics of anthracene which reacts mostly with ultraviolet radiation. In the application of the method it is assumed that the relationship between the integrated radiation and the concentration of anthracene does not change inside and outside the canopy. Although the regression of Eq.(1) is derived on the basis of the relationship between the concentration and photon flux density, illuminance, or total irradiance outside the canopy, in some cases the relationship may not be applied within the canopy. For analyzing the light environment in more detail, the assumption should be tested carefully.

Various apparatus can also be developed for use in different field experiments. We described a method using vials, strings and rubber bands. Although the vials were located with their caps upward, it is likely that the caps intercepted only part of the radiation coming from above due to the nearly continuous swing of the vials. Methods can be developed using other instruments which are more suitable for particular conditions and can be applied to various measurements of the light environment.

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