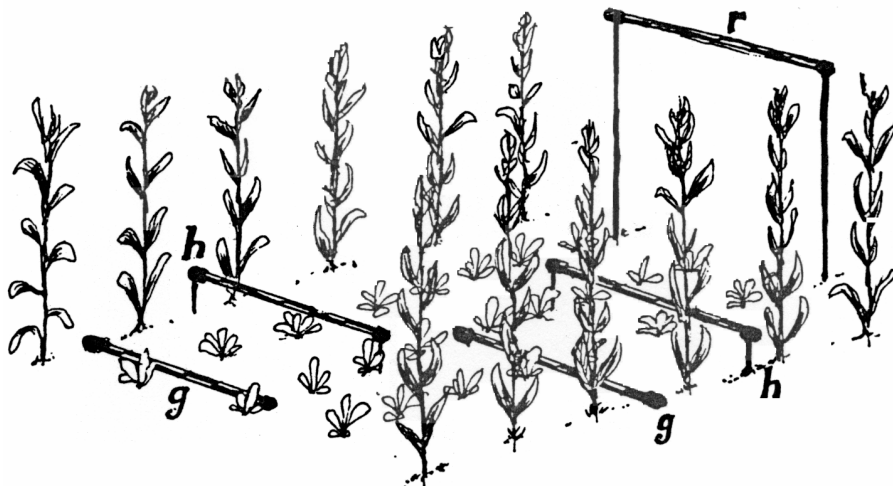

Applications Note: TSL-AN-4-1

Using Tube Solarimeters to
Measure Radiation
Intercepted by Crop Canopies
and to Analyse Stand Growth.

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DELTA-T DEVICES

APPLICATIONS NOTE

USING TUBE SOLARIMETERS TO MEASURE RADIATION INTERCEPTED BY CROP CANOPIES AND TO ANALYSE STAND GROWTH

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This note gives a brief history of procedures for analysing the growth of crop stands, leading to a relation between intercepted radiation and biomass. Analysis of measurements with tube solarimeters throughout the growing season is discussed and theory linking the interception of total solar radiation to the interception of quanta is outlined.

Practical aspects include the exposure and calibration of tube solarimeters and examples are given for different types of stand including mixed communities.

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EVOLUTION OF GROWTH ANALYSIS

How does the growth of a stand of vegetation depend on the weather to which it is exposed, hour by hour and day by day? Ecologists and agronomists have been trying to answer this question for almost 200 years - and they are still trying! Difficulties are obvious: the variability of weather in time and of plants in space; the complex response to weather of all physiological processes; the interaction of weather with pests, diseases and nutrient deficiencies.

Over the past 70 years or so, progress has been made in three main directions. First, a scheme of "Growth Analysis" was developed and used to correlate attributes of growth with elements such as rainfall, daily mean temperature, radiation, etc., measured at standard climatological stations. Second, instruments were devised to measure elements of the microclimate within plants stands. Finally, sets of equations describing how plants respond to weather were combined in "models" that could be used to predict growth and yield in a prescribed environment.

The main element of Growth Analysis as developed by D.J. Watson (1958) was a Net Assimilation Rate (NAR) - the rate at which the biomass of a plant stand increased per unit field area. Agronomists made many attempts to correlate NAR with individual elements of weather but this type of analysis was usually inconclusive, partly because NAR decreases as biomass increases and partly because measurements of biomass accumulation in the latter part of the growing season are prone to very large errors.

Little use is now made of NAR in the analysis of crop growth but one of its components - Leaf Area Index (LAI) - has proved invaluable in many contexts from modelling the growth of vegetation to the interpretation of satellite images. LAI is defined as the total plan area of all leaves per unit ground area.

2. THE BIOMASS/RADIATION RELATION

History

In the early 1950s, Professor Monsi and his colleagues in Japan started working on models of crop photosynthesis that described how solar radiation penetrated a stand of vegetation to be absorbed and scattered by leaves. To measure mean horizontal irradiance as a function of depth within foliage, Isobe (1962) developed a simple tubular solarimeter. This idea was taken up by Szeicz et al. (1964) who used the Wilson and Epps (1920) technique of plating constantan wire with copper to make linear thermopiles that fitted into glass tubes, about 90 cm long and 2 cm in diameter.

In the 1960s and early 70s, no commercial tube solarimeters were available but laboratory-made instruments were exposed in a number of arable crops. Delta-T tube solarimeters, similar in format to those of Szeicz et al.,

appeared on the market in 1974. The substantial number of measurements collected from these and comparable instruments all confirmed that standing biomass of annual crops was effectively proportional to the amount of radiation intercepted by foliage from emergence until the onset of senescence at the end of the main growth period. This relation had already been demonstrated with conventional solarimeters and light meters as used by Shibles and Weber (1965) working with soybean, Williams et al. (1965) with maize and Baker and Meyer (1966) with cotton. Warren Wilson (1967) used the relation to define an efficiency of light use by field crops and the consistency of this quantity for diverse British crops was demonstrated by Monteith (1977) and by Gallagher and Biscoe (1978).

An important consequence of all this work was that traditional Growth Analysis in terms of a Net Assimilation Rate could be replaced by a new straightforward type of analysis in which plant growth is a simple function of (i) the amount of radiation intercepted over the growing season; and (ii) the amount of dry matter produced per unit of radiation intercepted (e). This latter quantity is often referred to as a "Radiation use efficiency" but it is not an efficiency (with a range from 0 to 1) in the strict physical sense and the term Biomass Radiation Coefficient (BRC) will be used in this document.

Determination of Biomass Radiation Coefficient

If $S(t)$ is solar irradiance (radiant energy per unit ground area and per unit time) on day t , $f(t)$ is the fraction of that energy intercepted (incident minus transmitted) by a canopy, and $e(t)$ is the corresponding value of the BRC, a general relation between standing biomass $W(D)$ on day D and radiation intercepted up to day D is

$$W(D) = \Sigma \{e(t).f(t).S(t)\}$$

where Σ represents summation from $t = 1$ to $t = D$. A mean value for e over D days can be defined by

$$e_m = W(D)/\Sigma \{f(D).S(D)\}$$

When $S(t)$ and $f(t)$ are not strongly correlated, the quantity $S(t)$ can be replaced by a seasonal mean value of S (S_m) so that

$$e_m = W(D)/\{S_m \Sigma f(D)\}$$

Early experience suggested that e_m usually fell within the range 1.0 to 1.6 g (dry matter)/MJ with C3 species at the lower end of the range and C4 species at the upper end. Eventually, crop physiologists began to compare the impact of stress on e_m with the impact on the interception of radiation. The available evidence suggests that most stresses reduce both the amount of radiation intercepted by foliage and the accumulation of dry matter per unit of intercepted radiation. However, the proportional change in e_m is usually smaller than the change in the seasonal total of intercepted radiation implying that the restricted supply of assimilate is not the only factor that inhibits leaf expansion. Examples can be found for drought (Singh and Sri Rama, 1989), foliar disease (Waggoner and

Berger, 1987), nitrogen deficiency (Green, 1987), and atmospheric pollution (Unsworth et al., 1984). Measurements of radiation interception have also been used to compare and analyse the yield of different cultivars in the same environment (Rosenthal and Gerik, 1991) to examine the dependence of radiation use efficiency on stage of development (Trapani et al., 1992), and to explore the impact of plant spacing and row geometry on biomass production and yield (Steiner, 1986).

This type of analysis bypasses the need to measure LAI in order to estimate NAR (or f) but the amounts of biomass invested by plants in leaves and in roots have major ecological significance. A central problem in the interpretation of vegetation images obtained by satellites is to estimate LAI and f from the spectral composition of reflected radiation and both quantities play a central role in ecosystem models (e.g. Woodward, 1987).

Demetriades-Shah et al. (1992) suggested that crude estimates of e for a whole growing season can be obtained by guessing how f changed during the season! In order to compare values of e and f between species, treatments or environments, it is clearly essential to measure intercepted radiation as a function of time throughout growth.

Differential Analysis

Suppose the interception of radiation has been measured over the growing season (a) in stands of the same cultivar on which different treatments are imposed (e.g. water, nutrients, disease protection); or (b) in stands of different cultivars exposed to the same environment. How should differences of e or $\Sigma f(n)S(n)$ between treatments or between cultivars be compared?

Rearranging the terms in equation (3) and taking logarithms gives

$$\ln \{W(D)\} = \ln (e_m) + \ln S_m + \ln \{\Sigma f(D)\}$$

If the symbol δ is used to represent the difference between the value of each term in the equation for a specified treatment (or cultivar) and the value for some standard treatment (or cultivar) taken as a reference, then the equation can be recast in the finite difference form

$$\delta \ln \{W(D)\} = \delta \ln (e_m) + \delta \ln \{\Sigma f(D)\}$$

where there is no term in S_m when the irradiance is the same for all treatments. The two terms on the right-hand side of the equation refer respectively to differences in efficiency and interception.

This procedure can be taken a step further if the economic yield of a crop Y can be expressed as the product of the final biomass $W(D)$ and a harvest index h . Then

$$\delta \ln (Y) = \delta \ln (e_m) + \delta \ln \{\Sigma f(D)\} + \delta \{\ln h\} \quad (6)$$

This equation can be plotted graphically as shown in Figure 1 to compare the contribution of each of the terms on the right hand side to differences in yield.

FIGURE 1

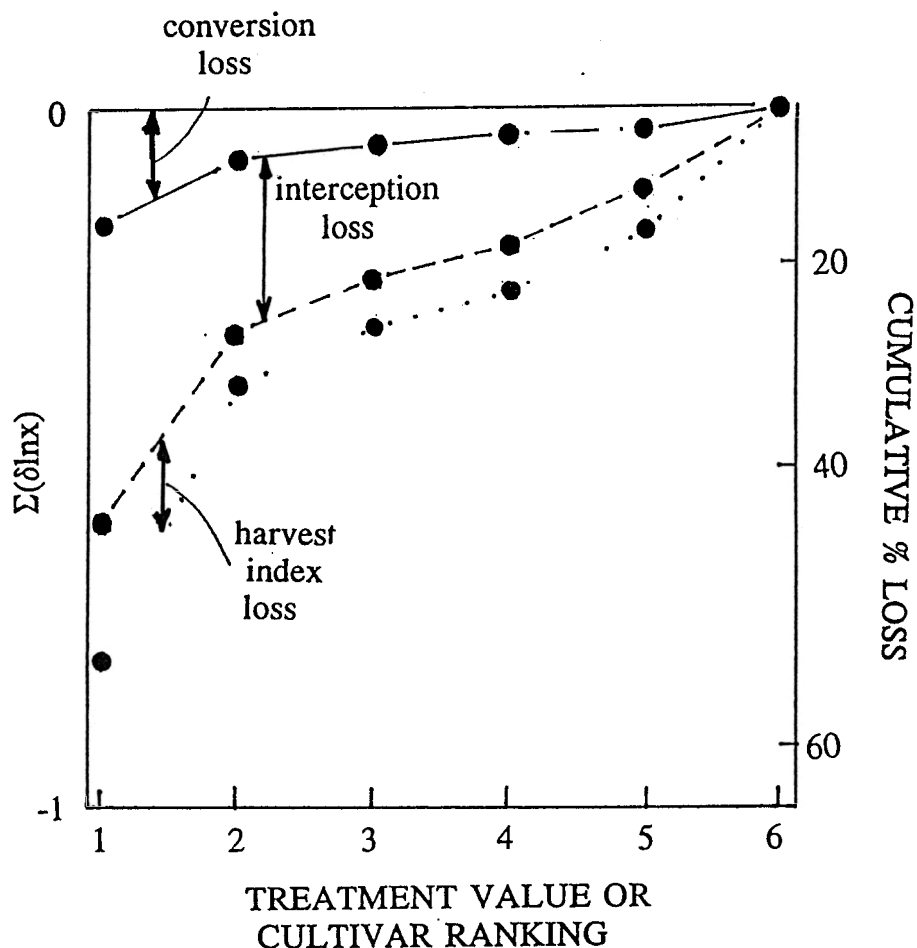


Fig.1 Graphical representation of eqn 6. The full line represents the first term on the right-hand of the equation and is the loss of conversion efficiency from energy to biomass (decrease of BRC). The dashed line is the sum of the first two terms so that the difference between the full and dashed lines is the loss of interception. Similarly, the difference between the dashed and dotted lines is the loss of harvest index. The left-hand vertical axis is the cumulative value of $\ln x$ where x is e, f or h and the right-hand axis displays this quantity as a cumulative percentage loss.

In this hypothetical example of how a cultivar might respond to a set of treatments (e.g. levels of water or nutrient supply), the major impact of the imposed variable is on light interception and therefore on the expansion of foliage. The BRC and the harvest index are almost independent of treatment between levels 2 and 5.

3. INTERCEPTION OF SOLAR RADIATION AND LIGHT QUANTA

Like solarimeters used by climatologists, the first tube solarimeters responded to radiation of all wavelengths transmitted by clear glass, i.e. from about 0.4 to 2 μm whereas photosynthesis responds to "photosynthetically active radiation" or PAR in the waveband 0.4 to 0.7 μm . In an attempt to measure PAR, Szeicz et al. (1974) used solarimeters in pairs, one of which was fitted with a gelatine filter that absorbed radiation above 0.75 μm . PAR could then be estimated by difference between plain and filtered tubes. Solarimeters of both types were originally made by Delta-T Devices but a neater solution to the problem is presented below and the use of filtered solarimeters is no longer necessary.

Strictly, the process of photosynthesis responds not to energy in the PAR waveband but to the number of quanta received per unit area and per unit time. Working in wheat stands that had received different levels of nitrogen, Green (1987) was able to show that there is a tight correlation between the interception of total energy and the interception of quanta. This is a consequence of the validity, in most uniform plant stands, of a simple Beer's Law relation between the transmission of radiation τ in a specified waveband and the leaf area of foliage above the level of measurement, i.e.

$$\tau = \exp(-KL)$$

where K is an extinction coefficient depending on wavelength, and on the optical and geometrical properties of leaves.

As a useful practical approximation, the ratio of K for PAR (or quanta) to K for the whole solar spectrum is given by the square root of the corresponding absorption coefficients for leaves (Goudriaan, 1977, Monteith and Unsworth, 1990, p. 91). In the PAR waveband, the absorptivity is often in the range 0.85 to 0.90 (McCree, 1972) compared with about 0.50 for total solar radiation. The corresponding range of ratios for K (visible) to K (total) is from 1.30 to 1.34. Green (1987), working with wheat, found that the ratio of K for quantum flux to total radiation flux was 1.35. However, very thick leaves with absorptivities of 0.9 (visible) and 0.6 (total) could have a K ratio of only 1.22. When it is important to determine the ratio of K values accurately, it may be possible to follow Green's procedure of plotting $\ln(\tau_q)$ (the fractional transmission of quanta) measured at different values of L against corresponding measurements of $\ln(\tau_T)$ (the fractional transmission of total solar radiation). If this procedure is not feasible, the absorptivity of individual leaves should be measured as a separate exercise.

To estimate quantum transmission using tube solarimeters, the value of K for total radiation (K_T) is found by measuring the mean fraction of incident total radiation below a leaf index of L (i.e. τ_T) and inverting the above equation to give

$$K_T = -\ln(\tau_T)/L$$

where \ln is a natural logarithm.

The fractional transmission of quanta is then given by

$$\tau_q = \exp (-1.35 K_T L) \quad (9)$$

$$= \tau_T^{1.35} \quad (10)$$

assuming Green's value for the ratio of K values.

Strictly, it is the fraction of incident quanta absorbed by foliage that determines rates of photosynthesis rather than the fraction intercepted. This is the complement of absorbed plus reflected radiation and $(1-\tau_q)$ is therefore an overestimate of absorbed quanta. However, the fraction of quanta reflected by a closed canopy is usually only 5 to 10% of incident radiation so that differences between fractional interception and fractional absorption are small. Comparisons obtained from models are given by Monteith and Unsworth (loc. cit. p. 90) and by Campbell and van Evert (1993).

4. INSTALLING TUBE SOLARIMETERS

Calibration and Exposure

A major advantage of using intercepted or absorbed radiation to analyse growth is that absolute measurements of incident radiation (S) can be made with a conventional solarimeter (e.g. as manufactured by Kipp or Eppley) and relative measurements (to give values of f) with tube solarimeters.

Delta-T Devices' tube solarimeters are supplied matched to a standard sensitivity, but where tubes are not, the following procedure can be used. In any case, it is good experimental practice to carry out such a check at the beginning and end of an experiment.

For calibration, all tube solarimeters in a set should be mounted well away from obstructions and to minimize errors of response that are unavoidable with cylindrical tubes (Szeicz et al., 1962), it is essential that they be parallel (within a few degrees) and horizontal. Outputs are then recorded over several days to determine relative sensitivity factors. It is convenient but not essential to select as a standard the instrument with the greatest sensitivity so that relative sensitivity factors are all less than unity. All subsequent measurements of output are divided by the appropriate sensitivity factor before calculating fractional transmission. Where the tubes are used with the Delta-T Logger type DL2, the sensitivities can be programmed into each channel at the start of the experiment, if preferred.

In use, the standard solarimeter is mounted on open ground near the site of the experiment or over the site itself above the maximum expected height of plants. Again, it is essential that all tubes should be parallel. It is also desirable that they be mounted N-S to minimize response errors when the sun is near the horizon; but for the sake of good spatial averaging, it is sometimes more important to choose a cross-row direction.

In systems where tubes are longer than the inter-row spacing, they should be angled with respect to the rows so that they fit exactly across the space between one or more rows (Fig. 2a). In systems where tubes are shorter than the inter-row spacing, they should be distributed to give a sample of transmitted radiation that is not biased by the pattern of shadows cast by rows (Fig. 2b). For example, in the northern hemisphere with E-W rows, solarimeters close to the N side of a row would receive less radiation than solarimeters to the S side so that measurements on both sides must be given equal weight.

Sampling and Replication

Because of the spatial variations that characterize all types of vegetation, the problem of obtaining representative values of intercepted or absorbed radiation in a stand are often formidable. When the end point of the exercise is a correlation between radiation and biomass accumulation, it is also necessary to obtain representative measurements of biomass.

One solution, attractive in theory but usually impractical, would be to sample radiation and biomass destructively at several points in a stand and then to move the tube solarimeters to another point. Then if the biomass sample was large or small in relation to the mean biomass, this anomaly would be offset by a corresponding anomaly in the radiation measurement. To avoid damage to the stand, however, and for other practical reasons, solarimeters are usually installed at several fixed points at the beginning of the growing season and radiation measurements are subject to systematic error through the season if the sites are not representative. Biomass, in contrast, is usually sampled over the whole stand at sites chosen randomly for each harvest.

In principle, random error in measuring intercepted or absorbed radiation can be minimized by maximizing the number of solarimeters in a trial. In practice, this number is usually determined by available resources rather than by the need to hold errors below some preset target value. Typically, for a trial plot (about 10 m square, say) three tubes would be used beneath the canopy, and for a field, between five and ten tubes, assuming a reasonably homogeneous crop stand.

Special problems of sampling arise in mixed communities (e.g. intercropping and agroforestry systems) where one species is much taller than another. Where rows of a tall species (T) are interplanted systematically with several rows of a short species (S), solarimeters should be mounted at representative places (r) just above T; (h) just above S; (g) below S. The interception of radiation by T is then given by the difference between (r) and (h) irradiances, and the interception by S is given by the difference between (h) and (g) irradiances (Fig. 3). Corlett et al. (1992) used this technique successfully in a leucaena/millet agroforestry system.

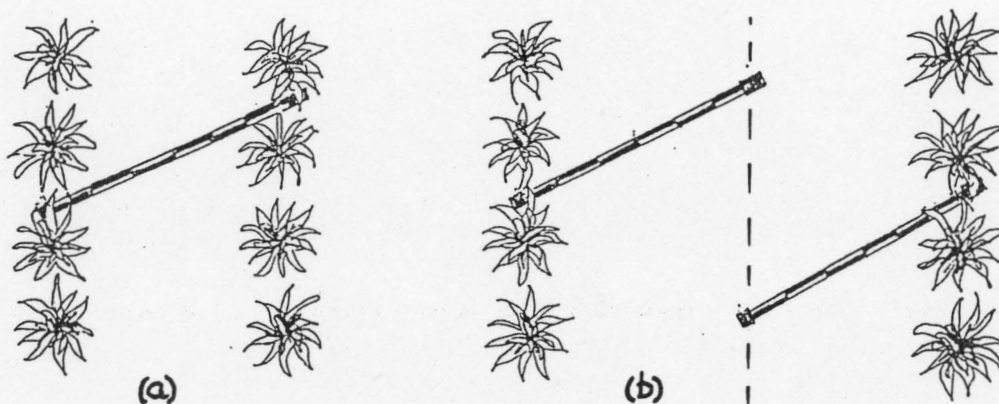


Fig. 2 (Plan view). Suggested arrangement of solarimeters:
(a) when row width is less than length of solarimeter,
(b) when it is greater.

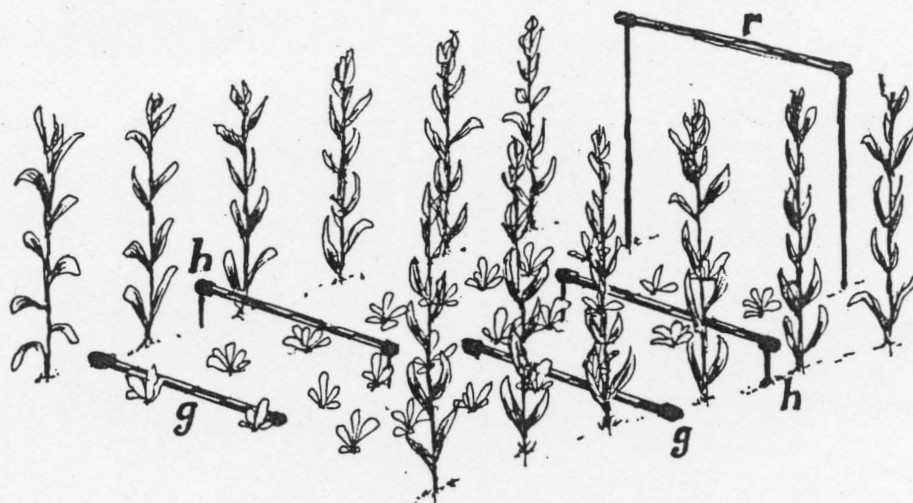


Fig.3 Suggested arrangement of solarimeters in a mixed community with three rows of a short-statured species between each row of a tall species (see p8).

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