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INTERCEPTION OF SOLAR RADIATION IN RED CLOVER CANOPIES AND THE INFLUENCE ON YIELD FORMATION – THEORETICAL AND PRACTICAL ASPECTS –

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Abstract

This paper presents the theoretical approach related to light interception and utilization in crop canopies. Practical examples consider the red clover canopy. The height of assimilatory surfaces, leaf architecture, reflection coefficient and extinction coefficient are important factors in the characterization of the efficiency of solar radiation utilization in crop canopies. Photosynthetically Active Radiation absorption becomes relatively constant from a leaf area index of 3.5, and the reflectance diminishes with leaf area increment.

Keywords: red clover, light interception, canopy structure, canopy, leaf area index

1. INTRODUCTION

Plant communities are aggregations of various species entities that compete within 3-D space to acquire vital resources (light, water and nutrients) in the vegetation season. Complex ecophysiological mechanisms exist between resources capture and plant responses, which engender modifications of canopy dynamics and root development patterns. Furthermore, canopy structure and crop growth are correlated because structure results from growth pattern of individual plants within the canopy (Dunea, 2008). At individual level, competitiveness depends on the deployment efficiency of morphological organs specialized to gain resources (leaf, root). Changes in morphological ratios often describe the sources of variability in the population structure (Allirand, 1998). Canopy - roots ratio is related to total biomass and leaves - stems ratio corresponds to above ground biomass. The plant’s architecture is independent of allocation trade-off and can be considered as a measure of how efficiently biomass is used. Spatial and temporal repartition of foliage biomass and caulinar biomass is influencing the evolution of canopy architecture.
Vertical and horizontal positioning of assimilatory areas (mainly leaves) depicts leaf area density (LAD), which is a spatial distribution parameter used in multi-layer mixed canopy models for calculating light profiles and absorption of light by species (Spitters and Aerts, 1983; Kropff and Van Laar, 1993). Asymmetry of leaf distribution within canopy amplifies with the kinetic of growth and the intraspecific competition for light.
Competition for light is an instantaneous process of resource capture and the efficiency of resource capture is related to light interception and light use characteristics of the species (Kropff and van Laar, 1993). Competition for light is significantly different from competition for water and nutrients, showing very few means of control in the crop field. Studying the biological impact of species on the capture and utilization efficiency of radiative resource offers support in weed control and breeding programs, which will help the creation of many competitive cultivars (Motcă *et al.*, 2007; Vîntu *et al.*, 2004).
Chlorophyll-containing organs can not fully use the incident radiations on the earth's surface, which are forming the solar spectrum. Photon energy conversion into chemical energy by photosynthetic system of leaves is made only for radiation wavelengths between 350 and 750 nm, with a highly variable efficiency in this range.
McCree (1972, 1973) proposed the range of 400-700 nm to define the radiation useful for photosynthesis. This interval is almost identical with the visible spectrum that is perceived by the human retina and is generally called light.
Visible spectrum is divided into seven colors - violet, indigo, blue, green, yellow, orange and red - ensuring that by combining them in certain proportions, the obtaining of white color.
The intervals are unequal in size, significant ones being blue-violet (400 to 505 nm), green (505 to 570 nm) and red (620 to 750 nm). Plants reflect mostly green and infrared radiation, which explains their green color and protects them from overheating due to infrared rays.
In literature, PAR (*Photosynthetically Active Radiation*) is the most often used term to characterize this radiation.

2. MATERIAL AND METHOD

In terms of interference with the crop canopy, solar radiation can be characterized by three variables:
- **R_g** = Global solar radiation expressed in energy units (W/m^2 in the period of time: hour, day, decade, etc.);
- **EPAR** = useful radiation for photosynthesis expressed in units of energy (J/m^2 or MJ/m^2 in the period of time: hour, day, decade, etc.) or the flow of energy;
- **QPAR** = useful radiation for photosynthesis expressed in number of photons (µmol·m^{-2}·s^{-1}) or photon flux intensity PPFD (Photosynthetic Photon Flux Density).

Each of these variables may be characterized by several indicators (Figure 1).

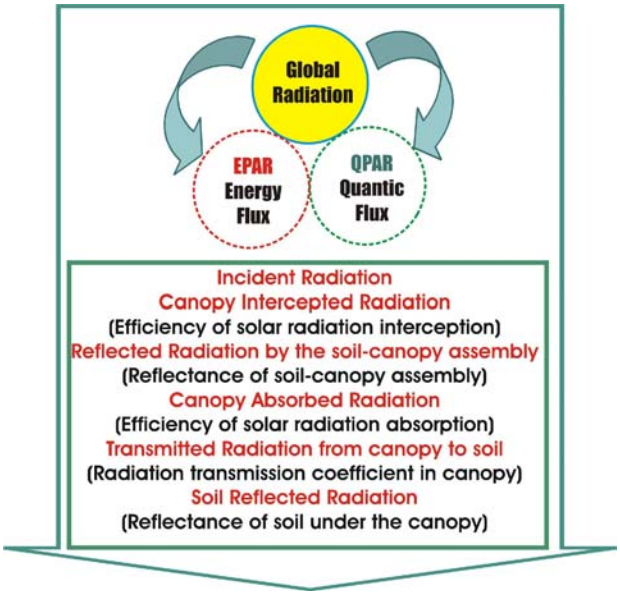

Figure 1. Main indicators quantifying the solar radiation availability for crop canopies

McCree has shown an optimal proportionality between the intensity of photosynthesis and PAR, when the PAR value is expressed as the number of photons and not by units of energy. Expression of PAR in energy values (Figure 2) is less satisfactory if the spectral composition of light changes, which commonly occurs in natural conditions (Varlet-Grancher *et al.*, 1981).

Interception of solar irradiance by a crop canopy results in both quantitative and qualitative changes in the photon flux, which may have impact on intraspecific and interspecific competition. The arrangement and orientation of the leaves within the canopy influences the proportion of PPFD that is absorbed by the canopy and the amount of PPFD per unit sunlit leaf area.

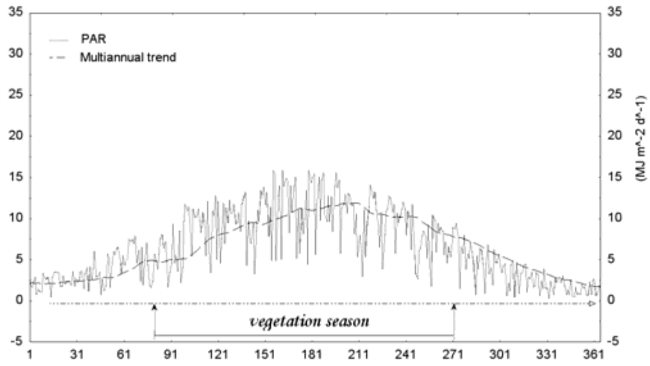

Figure 2. EPAR time series and multi-annual trend in Targoviste plain - useful radiation for photosynthesis expressed in units of energy (MJ/m^2)

There are several relationships to be considered for each of the three variables in order to achieve the radiative balance of the canopy characteristic of a species grown in pure stand (Table 1).

Table 1 Basic relations used to study the radiative balance in crop canopies (* *I = Rg, EPAR or QPAR*)

Indicator	*Total Radiation* (I)*
Incident Radiation	I_0
Transmitted Radiation from canopy to soil	I_t
Reflected Radiation by the soil-canopy assembly	I_r
Soil Reflected Radiation	I_{rs}
Canopy Absorbed Radiation	$I_a = I_0 - I_r - I_t + I_{rs}$
Canopy Intercepted Radiation	$I_i = I_0 - I_t$
Radiation transmission coefficient in canopy	$T = I_t / I_0$
Reflectance of soil-canopy assembly	$I = I_r / I_0$
Reflectance of soil under the canopy	$I_s = I_{rs} / I_t$
Efficiency of solar radiation absorption	$\varepsilon_a = 1 - I - T + I_s \times T$
Efficiency of solar radiation interception	$\varepsilon_i = 1 - T$

In the case of plants' associations (cultivated species-weeds, legume-grass mixtures, polycultures or multiple cropping systems), interception of light in canopies is mainly influenced by the leaf area index (LAI), the leaf area height and absorption characteristics of each component species.

Higher positioned leaf layers absorb and reflect a greater amount of radiation compared with those located below them.

Light absorption characteristics of species depend on optical properties, thickness and goniometric distribution of leaves.

This distribution determines the amount of radiation absorbed per unit of leaf area. Planophile leaf species (e.g. legumes) captures light more efficiently than erectophile canopies (e.g. perennial grasses). However, canopy photosynthetic efficiency will be significantly higher in erectophile than in planophile canopies at similar PPFD absorption rates. The leaves absorb a small amount of near infrared radiation. Calculated values for the efficiency of global radiation are lower than those obtained for the radiation useful for photosynthesis. It is estimated that from the total quantity of light on a leaf (100%), 1.5 to 3.0% is used in the process of photosynthesis, and the rest is reflected, is passing through the leaf, is lost as heat or is used in the transpiration process as latent heat of vaporization. The absorption of PPFD by leaves is by the chloroplast pigments, such as chlorophyll *a* and *b* and some of the carotenoids. Depending on the intensity of light, chloroplasts move to settle with the longitudinal axis or in a transverse position in direction of the radiation source. Light absorption follows the Stark-Einstein law, which states that each pigment molecule can absorb at one time a single photon and this photon can excite only one electron. The mechanism of photosynthesis process was presented in detail by Burzo *et al.* (1999). Approximately 90% of incident PPFD is absorbed by green leaves, with lower proportions for young or senescent leaves. Drought induced changes in leaf optical properties and orientation of the visible spectrum to the absorption of infrared radiation. Radiative fluxes above and within vegetation cover have direct influence on the CO_2 assimilation by the plant species. Daily solar radiation (300-3000 nm) measured or estimated by different methods is used as the primary input in order to model light interception and absorption by the crop canopy. It is considered that approximately half (0.48) of this amount represents PAR (400-700 nm). This fraction is used in model procedures estimating CO_2 assimilation rates in uniform canopies (Goudriaan, 1977). Modeling the light interception process in mixed canopies is a reliable method determining the coefficient of light utilization for each species in plant association. Since there are many factors involved in assessing the processes that determine the competition for light, evaluation of the photosynthetic and morphological characteristics role on solar energy bioconversion efficiency is performed by mechanistic models developed in the last two decades (Spitters and Aerts, 1983, Kropff and Spitters, 1992, Graf *et al.*, 1990), especially the model INTERCOM (Kropff and van Laar, 1993) which extends the classical calculation algorithms of light absorption in monocultures.

3. RESULTS AND DISCUSSIONS

The light profile of photosynthetically active radiation (PAR) can be determined making samplings by using a ceptometer (e.g. Delta–T SunScan Canopy Analysis System Delta-T Devices Ltd., Cambridge, UK) at successive layers of 10-40 cm (depending on species height) in the canopy from ground to top level. PAR measurements are repeated several times at each layer in different positions of the canopy to improve the accuracy of the light-extinction profile.

CANOPY LIGHT INTERCEPTION AND ABSORPTION ESTIMATION

At the terrestrial surface, the intensity of radiation depends on the angle of incidence, as shown in figure 3.

The figure shows that at ΔL = ct, and a variable angle alpha with the vertical, increasing ΔS areas are obtained, tending from $\alpha = 0$ to ∞.

Consequently, the density of radiation is reduced to zero, as is the case of sunrise and sunset, or in winter. The correlation between the amount of radiant energy received at the ground and the angles of incidence of solar rays is expressed by Lambert's relations:

$$I' = I \cos \alpha, \text{ sau } I' = I \sin \varphi \qquad (1)$$

where:

I' - the amount of energy received at angle φ or α;

I - maximum energy (rays perpendicular to the ground);

α - zenith angle formed by the ray with the perpendicular to the ground;

φ - sun height angle to the horizontal.

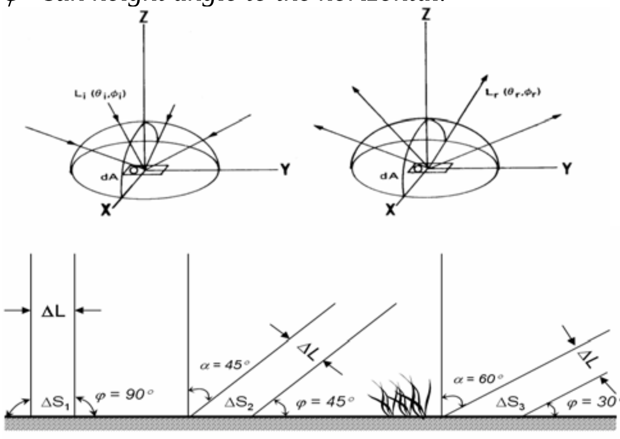

Figure 3. Radiation intensity at ground level depending on the angle of incidence of solar rays.

Leaf angle distribution on the ellipsoid (*ELADP*) must be calculated in order to determine the extinction coefficient (*k*) of a species. This parameter describes the tendency of leaves towards horizontal or vertical orientation:

$$x = ELADP = \frac{N_h \cdot \pi}{N_v \cdot 2} \qquad (2)$$

where:
N_h – *number of horizontal leaves* (>45° to vertical);
N_v – *number of vertical leaves* (<45° to vertical).

The coefficient *k* is determined as a function of *ELADP* (x) and zenith angle of direct incident radiation (θ), as follows:

$$k(x,\theta) = \frac{\sqrt{x^2 + \tan^2\theta}}{x + 1.702 \cdot (x + 1.12)^{-0.708}} \qquad (3)$$

The mean value obtained for *k* must be used to assess the energy transmitted to the canopy according to Beer's law, as a function of the leaf area index:

$$I = I_0 \exp(-k \cdot LAI) \qquad (4)$$

where:
I - the energy transmitted in crop canopy;
I_0 *- incident solar radiation;*
k – light extinction coefficient of PAR in canopy;
LAI - Leaf Area Index.

Incident radiation is partially reflected with reflectance coefficient (ρ) by the crop canopy, which is a combination of randomly distributed green leaflets. ρ indicates the fraction of radiative flux which is reflected by the canopy (equation 5 - Goudriaan, 1977).

$$I = (1-\rho) I_0 \exp(-k \cdot LAI) \qquad (5)$$

Fraction (1-ρ) of incident radiation in the visible spectrum expresses light absorption in the canopy. Radiative flux exponentially decreases inside the canopy together with cumulated LAI from the top to the ground (equation 6):

$$\rho = \left[\frac{1-\sqrt{(1-\sigma)}}{1+\sqrt{(1-\sigma)}}\right] \cdot \left[\frac{2}{1+1.6\sin\theta}\right] \qquad (6)$$

where:
ρ *- reflectance factor;*
σ *- light diffusion coefficient characteristic for individual leaves (σ = 0.2 - average for most cultivated species);*
θ *- zenith angle of direct incident radiation.*

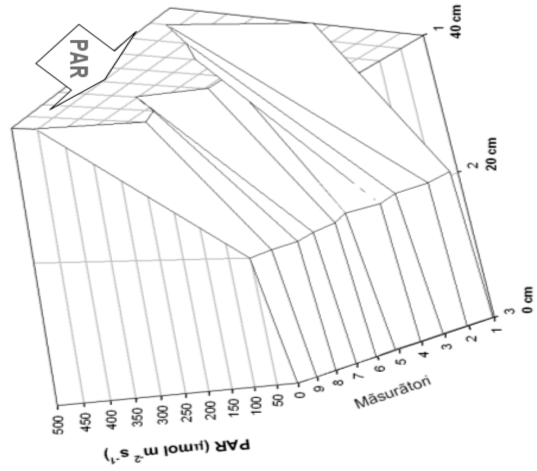

Figure 4. PPFD Radiative flux (μmol·m^{-2}·s^{-1}) in red clover canopy

Figure 4 highlights the process of PPFD flux inside red clover canopy measured from top layers to the ground.
Light absorption coefficient of the red clover foliage is 0.86 (Dunea, 2006). Photosynthetically Active Radiation absorption becomes relatively constant from a leaf area index of 3.5, and the reflectance diminishes with leaf area increment (fig.5)
In conditions of high radiation intensity, the direct fractions rarely pass the 80% of the total incident radiation, so that the diffused component is important for the absorption capacity of the canopy. Diffused light does not correspond to the Beer's law curve and, excepting horizontal leaf distribution, cannot be described with a singular light extinction coefficient.

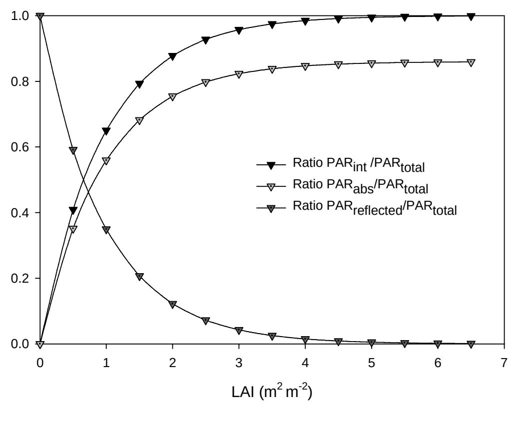

Figure 5. General trends of the radiative parameters in function of Leaf Area Index for red clover (*Trifolium pratense* L.)

A significant diffused radiation amount was observed in red clover canopy (fig. 6). LSD test (99.99%) provided significant differences between different canopy layers: 40/20 cm (-7.8 μmol m^{-2} s^{-1}), 40/0 cm (-28.05 μmol m^{-2} s^{-1}) and 20/0 cm (-20.25 μmol m^{-2} s^{-1}).

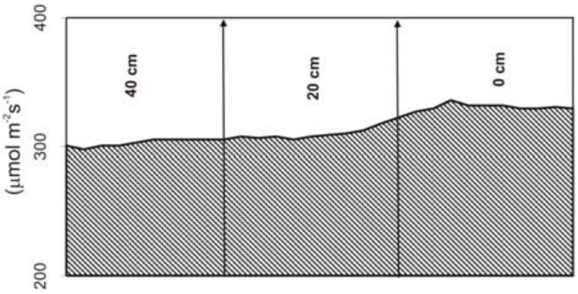

Figure 6. Diffused Radiation (μmol m^{-2} s^{-1}) in red clover canopy for different layers from top to the ground

Red clover canopy captures a higher proportion of available energy in the upper layers, which predominantly contain leaf surfaces characterized by superior light absorption and extinction coefficients.

4. CONCLUSIONS

The interception of the photosynthetically active radiations by the foliar system depends on the Leaf Area Index. In red clover, LAI values of 3-4 are sufficient for the reception of light, but LAIs of 7-11 are required to obtain relevant productions (dry matter accumulations) depending on species and cultivar characteristics. LAI values are positively correlated with the crop growth rate (dry matter production per land area unit) for many cultivated species.

An eco-physiological model adapted to simulate the processes that characterize the potential production must take into account not only the leaf area index, but the light extinction coefficient, which gives a better estimate of the amount of absorbed Photosynthetically Active Radiation (PAR).

The height of assimilatory surfaces, leaf architecture, reflection coefficient and extinction coefficient are important factors in the characterization of the light interception and of the efficiency of intercepted radiation utilization in crop canopies.

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