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Solar Radiation Utilization by Tropical Forage Grasses: Light Interception and Use Efficiency

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1. Introduction

Neotropical grasslands or savannas cover almost half the surface of Africa and large areas of Australia, South America, India and Southeast Asia (FAO, 2010). In South America vegetation like savanna covers over 2.1 million km² mainly in central Brazil (also called Cerrado), Colombia and Venezuela. Tropical savannas are currently undergoing rapid and radical transformation due to human interventions on land-use patterns (Lehmann et al., 2009). In the last 30 years about 54 million hectares of native Cerrado vegetation have been replaced by cultivated pasture, mainly African grasses of the genus *Brachiaria* spp. (Boddey et al., 2004, Meirelles et al., 2011). At the same time, the majority of deforested land in the Amazon Basin has become cattle pasture, making forest-to-pasture conversion an important contributor to the carbon and climate dynamics of the region (Asner et al., 2004). The terminology here follows the International Forage and Grazing Terminology Committee (Allen et al., 2011): “the term grassland bridges pastureland and rangeland and may be either a natural or an imposed ecosystem. Grassland has evolved to imply broad interpretation for lands committed to a forage use”.

At present it is unclear whether neotropical grasslands are governed by the same factors in Australia, Africa and South America, the three major continental regions of this biome (Lehmann et al., 2009). What is clear is that significant portions of native or cultivated grasslands on every continent have been degraded due to human activities (FAO, 2010). In the tropical regions of Brazil where it is estimated at least half of the cultivated pastures are degraded, the two main drivers of degradation processes are low soil fertility (especially low soil N) and excessively high animal stocking rates (Boddey et al., 2004). On a global scale, overgrazing alone can account for about 7.5 percent of grassland degradation (FAO, 2010).

There is consensus that the sustainability of pastoral ecosystems demands more appropriate livestock management practices. Besides, for the ecological management of these agro-systems, it is necessary to increase the level of understanding of the interactions between its biotic and abiotic components. Central to this understanding, the diverse facets of the interaction between solar radiation and grassland vegetation is of theoretical and practical importance. They are the subject of this chapter, and range from forage grass as

monocultures to the complex interrelationships that exists among trees and grasses in silvipastoral agro-systems. In this chapter we will explore a few selected subjects within this broad chain of processes. Recently, focusing on the role of theory in plant science, Woodward (2011) noted that “the development of plant science is based on observations, the development of theories to explain these observations and the testing of these theories.” Besides the need of theory to overcome empirical approaches, the theoretical basis is also functional for a better understanding of possibilities and limitations of the new available instrumentation from advances in remote sensing and other technologies for grassland monitoring and assessment. We give emphasis to the concept of sward canopy structure, discussing the central role of Leaf Area Index in the pasture trophic program via light interception. We also give some theoretical and practical emphasis on methodological aspects and procedures for measurements of canopy structure and radiation interception by vegetation. And finally we considered the efficiency use of radiation.

2. Leaf Area Index (LAI) and the G-function: Theoretical considerations

Before talking more specifically about leaf area index and radiation interception as key variables of pasture ecosystems, we need to review some basic concepts about electromagnetic nature of solar radiation underlying the discussion on theoretical and practical aspects of sward canopy structure.

2.1 Some solar radiation concepts

Energy is transferred by electromagnetic waves characterized by wavelength and frequency. The electromagnetic spectrum ranges from high frequency cosmic radiation to low frequency radio waves. For practical purposes the solar spectrum reaching the Earth comprises mostly the ultraviolet, visible and infrared radiation. The spectral regions of the solar spectrum are listed in Table 1.

Spectral region	Spectral range (nm)
Ultraviolet	10 to 400
Visible	400 to 700
Infrared	700 to 4000

Table 1. Spectral ranges of solar radiation with wavelengths in nanometers units (1nm = 10⁻⁹ m).

The solar infrared radiation beyond 4000 nm that reaches the Earth is insignificant compared to that from 250 to 4000 nm. A few terms regarding solar radiation are considered here. The spectral region from 400 nm to 700 nm is also referred as the *photosynthetically active radiation* (PAR) as this is the region used by plants for photosynthesis. The region from 700 nm to 3000 nm is the reflected infrared, because the surfaces at the environment temperature do not emit in this part of the spectrum and from 1100 nm to 3000 nm is referred as the shortwave infrared.

The corpuscular theory of light is also of interest. It relates the amount of energy of the electromagnetic radiation in Joules (J) to a given wavelength. A quantum of energy is the amount of energy of a photon (a package of discrete energy of a single frequency) and is

given by $E = h \cdot \nu$, where h is the Planck's constant (6.626×10^{-34} J.s) and ν is the frequency in Hertz. In the PAR region it is of interest to use the units of mol photon $\text{m}^{-2}\text{s}^{-1}$. If the sun is the radiation source of the PAR, 1 MJ m^{-2} is equivalent to 4.6 mol photon $\text{m}^{-2}\text{s}^{-1}$ (Norman & Arkebauer, 1991).

The amount of energy that reaches a surface per unit area per time is called *irradiance* (E) and its unit is Watts per square meter (Wm^{-2}) being $1.0\text{W} = 1.0\text{Js}^{-1}$. The *radiance* (L) is the flux density per area and per solid angle in steradian (sr) and has units of $\text{Wm}^{-2}\text{sr}^{-1}$. These two are related as $E = \pi L$ where π is the integral of a projected solid angle over the upper hemisphere, in units of sr. The *solar constant* is the amount of energy coming from the sun that reaches the Earth outside the atmosphere for a distance sun-Earth of 1 (one) Astronomical Unit (UA, the average distance between the sun and the Earth). The solar constant was determined by the World Meteorological Organization (WMO) as 1367Wm^{-2} . From the total radiation at the top of the atmosphere 534.7Wm^{-2} is in the PAR region.

In order to illustrate the distribution of this radiation we performed calculations for the day 23rd of September 2011 at PESAGRO weather station in Seropédica ($22^\circ 45' 28.37''\text{S}$ and $43^\circ 41' 5.47''\text{W}$, Rio de Janeiro State, Brazil), at 13 UT (Universal Time). The sun-Earth distance was 1.0031UA and *solar zenith angle* (SZA, the angle from the sun direction to the vertical direction right above) was 34.4° . Considering the correction for the SZA the actual value of incoming radiation at the top of the atmosphere on a surface parallel to the Earth's surface was 1127.7Wm^{-2} . Using the 6S model (Vermote et al., 1997) we found that the *total global* (from 250 to 4000 nm, *direct plus diffuse*) irradiance on a horizontal surface on the ground was 796.1Wm^{-2} , which corresponds to 70.6% of the total radiation at the top of the atmosphere. From this amount of radiation reaching the horizontal surface, 356.2Wm^{-2} was in the PAR region. The surface incoming PAR in that condition was 68.9% from direct beam and 31.1% from diffuse sky irradiance. If the surface is perpendicular to the solar beam the incoming direct irradiance in the PAR region was 298.8Wm^{-2} , i.e., the transmission of PAR direct beam was 67.7%. These calculations using the 6S model considered a clear sky condition, tropical atmospheric model and continental aerosol model, with horizontal visibility of 15 km and target altitude of 34 m.

The incoming radiation on a plant canopy can be reflected, absorbed or transmitted to the soil background. From the conservation of energy it follows that the *incident energy* ($E_{i\lambda}$) is equal to the sum of the *reflected* ($E_{r\lambda}$), *absorbed* ($E_{a\lambda}$) and *transmitted* ($E_{t\lambda}$) fluxes:

$$E_{i\lambda} = E_{r\lambda} + E_{a\lambda} + E_{t\lambda} \quad (1)$$

Dividing these by the *incident energy*:

$$1 = \rho_\lambda + \alpha_\lambda + \tau_\lambda \quad (2)$$

where ρ_λ , α_λ and τ_λ are respectively the spectral *reflectance*, *absorbance* and *transmittance*. For remote sensing purposes it is considered the bidirectional reflectance, which is defined as reflectance acquired from a reflected directional flux divided by the directional incoming flux (Nicodemus et al., 1977). This is attained because the radiance that reaches the sensor is directional and under clear sky condition, the incoming flux can be considered a direct radiation flux.

2.2 Canopy structure definitions

According to Campbell & Norman (1989) “plant canopy structure is the spatial arrangement of above-ground organs of plants in a plant community” and as such includes the size, shape and orientation of all aboveground plant organs, making quantitative descriptions exceedingly difficult (Nobel et al., 1993). In practice, the leaf canopy structure of a plant community can be described in terms of *Leaf Area Index* (LAI), *leaf angle distribution* (LAD) and *leaf clumpiness*. The LAI concept was originally introduced by Watson in 1947 and is the one side leaf area per unit area of soil ($\text{m}^2 \text{ leaf m}^{-2} \text{ ground surface}$) and can be regarded as the number of leaf layers arranged above the ground. The LAD is the probability density of a leaf being in a certain angle in relation to the horizontal (or the leaf normal to the vertical). Clumpiness is related to how the leaves are distributed in the space. Area index, angle distribution and clumpiness can also be defined for stems (for stem area: SAI; for angle distribution: SAD) or any other aerial parts of the plant. Theoretical functions have been used in the literature to describe LAD for most situations present in nature, like those introduced by Wit (1965). It was expanded by Bunnik (1978) by adding the uniform and spherical types of LAD, which can be seen in Figure 1. Here a uniform distribution in azimuth is assumed, which means that the normal to the leaves are random regarding to the azimuth.

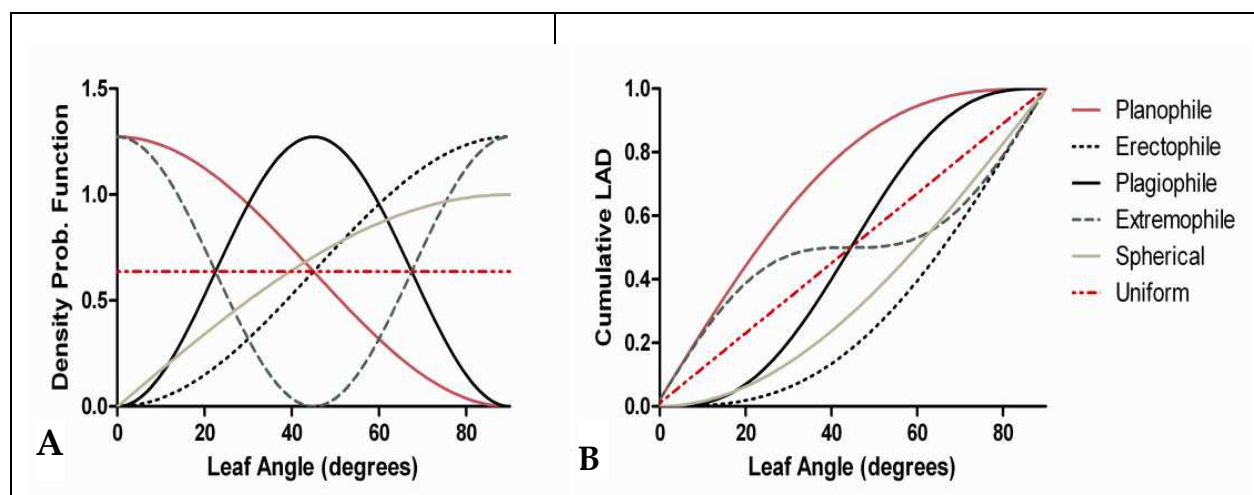


Fig. 1. Theoretical leaf angle distribution (LAD) of Bunnik (1978) for canopies. A) Density probability functions of leaf angle. B) Cumulative LAD.

The LAD represents the strategies that plants use to intercept radiation for plant processes. A planophile plant has most of the leaves near the horizontal and has a small variation of intercepted radiation for a range of solar zenith angles below 45 degrees. Erectophile canopies on the other hand, have large variations in interception and the gap fraction (fraction of openings in the canopy) is more frequent from close to nadir viewing. This way less radiation is intercepted when the sun is close to the zenith. Plagiophile canopies have most of the leaves around 45 degrees and conversely the extremophile canopies have most of the leaves around 0 and 90 degrees (respectively horizontal and vertical). The radiation interception by the extremophile canopy can lead to different results for the plant if the horizontal and vertical leaves are in different canopy layers.

The extinction of solar radiation by interception was initially described by Monsi & Saeki (1953, in English translation 2005) for horizontal leaf layers and generalized by Ross & Nilson in 1966 (Ross, 1981) to include leaf orientations other than horizontal. The rate of change of a downward direct flux of radiation (I_D) with the cumulative LAI at any height from the top of canopy is given by:

$$dI_D / dLAI = -\lambda_0 K_D I_D \quad (3)$$

where λ_0 is the leaf spatial distribution parameter, which is equal to 1 for leaf elements randomly distributed and leaf position is independent of other leaf positions, also referred as a Poisson canopy (Nilson, 1971, Baret et al., 1993). K_D is the *interception coefficient*, and is given by (Ross, 1981):

$$K_D = G(\theta_i, \theta_l, \varphi_i, \varphi_l) / \cos\theta_i \quad (4)$$

where $G(\theta_i, \theta_l, \varphi_i, \varphi_l)$ is the G-function, θ_i is the solar zenith angle, φ_i is the solar azimuth, φ_l is the leaf azimuth in relation to the solar azimuth, and θ_l is the leaf normal angle from the zenith direction, i.e., a vertical leaf has $\theta_l = \pi/2$ and a horizontal leaf has $\theta_l = 0$. The G-function represents the projected fraction of leaf area in the solar direction and is equal to the average value of the cosine of the angle between the solar zenith angle and the leaf normal angle (θ_l) from the vertical.

Assuming that leaves have a random azimuth orientation (Ross, 1981), meaning that normal to the leaves are random regarding to the azimuth, the G-function is calculated as (Ross, 1981, Antunes, 1997):

$$G(\theta_i, \theta_l, \varphi_i, \varphi_l) = \int_0^{\pi/2} g'(\theta_l) \int_0^{2\pi} \frac{|\cos\delta|}{2\pi} d\theta_l d\varphi_l \quad (5)$$

where $g'(\theta_l)$ is the density probability of leaf angle between 0 and $\pi/2$ and δ is the angle between leaf normal and the sun. The cosine of δ is calculated as (Ross, 1981):

$$\cos\delta = \cos\theta_i \cos\theta_l - \sin\theta_i \sin\theta_l \cos\varphi_l \quad (6)$$

The spherical LAD is of special interest because the leaves are arranged in such a way in the canopy that the leaves from one square meter of soil can fit a surface of a sphere with the same area as the LAI. As a result, at any solar zenith angle, the fraction of leaf area projected towards the sun is always the same, which is 0.5. This means that the G-function for such a canopy is always 0.5 regardless of the sun's orientation. Maize canopy LAD has been measured in the field and found to be spherical (Antunes et al., 2001). Plants with a spherical LAD intercept the same amount of radiation regardless the direction of the solar beam and can be regarded as a good characteristic for a high productivity canopy.

Equation 3 can be solved by integrating for an entire layer of canopy yielding:

$$I_D = I_0 \exp(-\lambda_0 G(\theta_i, \theta_l, \varphi_i, \varphi_l) LAI / \cos\theta_i) \quad (7)$$

where I_0 is the direct beam flux intensity at the top of the canopy, which can be set to be the fraction of direct beam above the canopy. In this equation the term $G(\theta_i, \theta_l, \varphi_i, \varphi_l) LAI / \cos\theta_i$ defines the mean number of contacts of the direct beam with the canopy elements (Nilson, 1971). Although the Equation 7 is similar to the Bouguer law (also referred as Beer's law) for

radiation transmission in a turbid medium, in which K is the attenuation coefficient, the concept as applied here is different from Beer's law, since this equation defines only the amount (or fraction) of direct beam left after passing through a canopy layer with a defined leaf area, LAD and clumpiness.

2.3 Direct and indirect methods for determining canopy structure

Canopy structure can be determined by direct methods or estimated through indirect methods. The direct methods involve the measurement of leaf area, angle and position of leaves in the canopy or by destructive sampling. A group of methods involve the measurement of leaf area with optical area meter devices, scanners, hand-held planimeters or weighing of paper replicates (Nobel et al., 1993, Asner et al., 2003). Generally these methods allow the computation, separately, of the form, size and number of leaves (Bréda, 2003). Another way to obtain leaf area is by correlating either green or dry biomass to leaf area to find a conversion factor i.e. the *specific leaf area* ($\text{m}^2 \text{kg}^{-1}$). All these methods give a standard reference for the calibration or evaluation of indirect methods of determining LAI (Bréda, 2003) or vegetation cover (Schut & Ketelaars, 2003). On the other hand leaf angle distribution and leaf clumpiness determination are restricted to on site observations as they need to be carried out in undisturbed canopies.

Direct methods are cumbersome and time demanding. As a result, the indirect methods have been largely used for estimating canopy structure. These methods use the relationship with other more easily measurable parameters, such as canopy transmittance, green cover estimate or correlation with dry or green biomass. Gap-fraction inversion is amply used to estimate LAI (Welles & Norman, 1991). Gaps are obtained from devices specially designed for this (e.g., LAI-2000^{*1}) or hemispherical photographs (e.g., CID 110^{*1}). The LAI-2000 finds the gap fraction at five angles, making it possible to estimate also the average leaf angle. Ceptometers are also used to estimate LAI through gap fraction (López-Lozano et al., 2009). Inversion of light transmitted through the canopy, measured by a line quantum sensor, has also been used to estimate plant area index, a composition of leaves and stems of the plants (Cohen et al., 1997). Hemispherical photographs are usually taken looking upward (Rich, 1990) and the digital processing allows the estimation not only the total gap fraction but also to partition these gaps in different angles. However, the indirect methods based on light extinction through the canopy can be affected by canopy structure assumptions, exceptionally regarding the clumping of leaves (Larsen & Kershaw, 1996).

A sensitivity analysis of the LAI estimation using the LAI-2000, a ceptometer (AccuPAR^{*1}) and hemispherical photographs was carried out by Garrigues et al. (2008), over 10 crops including pasture grasses. They found that the hemispherical photographs were the most robust technique, from many standpoints of evaluation, the least sensible to illumination conditions and thus can be applied for a large range of canopy structures.

2.4 Remote sensing of forage grasses

The use of remotely sensed data for monitoring forage grasses is of great interest due to its possibility of monitoring large areas and the broad range of sensors available, with varying

^{*1} The mention of a trademark does not constitute an endorsement by the Federal Rural University of Rio de Janeiro of these products and does not imply approval for the exclusion of other suitable products.

spatial, spectral, temporal and radiometric resolutions. Remote sensing is also cost effective for monitoring large areas as it drastically reduces field work compared to *in situ* samplings. The rationale behind the use of remote sensing for vegetation monitoring relies on the fact that leaf reflectance varies throughout the solar spectrum (Knipling, 1970). The combination of leaf properties with the canopy structure and sun-viewing orientation lead to complex interactions that causes varying reflectance values at each spectral region, e.g., see Ollinger (2011) for a review.

Grass canopy biophysical properties and the illumination/viewing geometry affect reflectance observed at surface level (Walter-Shea et al, 1992). At the satellite level the reflectance values calculated from the radiance reaching the sensor undergoes the effects from the atmosphere, soil and litter background, canopy structure, bidirectional anisotropy, spatial heterogeneity, nonlinear mixing and topography (Myneni et al., 1995). These effects make it much more complex to establish fixed relationships between canopy parameters (like LAI) and canopy reflectance. Despite this limitation, remote sensing has been largely used for monitoring and canopy parameter estimation. Two approaches that have been largely used to estimate canopy parameters from remotely sensed data, involve the use of vegetation indices and inversion of canopy radiative transfer models.

2.4.1 Vegetation indices

Vegetation indices are band combinations of remotely sensed data that have some relation with canopy parameters. The first introduced was the *simple ratio vegetation index* (SR or RVI) between the reflectance of near infrared band (ρ_{NIR}) and the reflectance of the red band (ρ_{red}). Many other indices have been introduced after the SR. The idea behind the indices was that they could remove soil background effects from remotely sensed data while keeping the high sensitivity of NIR reflectance to canopy LAI. The commonly used vegetation index is the *normalized difference vegetation index* (NDVI), which is given by:

$$NDVI = \frac{\rho_{NIR} - \rho_{red}}{\rho_{NIR} + \rho_{red}} \quad (8)$$

One index that has been used is the *soil adjusted vegetation index* (SAVI), which is calculated through the following equation (Huete, 1988):

$$SAVI = \frac{(1+L) * (\rho_{NIR} - \rho_{red})}{\rho_{NIR} + \rho_{red} + L} \quad (9)$$

where L is the canopy background adjustment factor. If L is disregarded SAVI reduces to NDVI. Vegetation indices are affected by the atmosphere (Myneni & Asrar, 1994). Thus Huete et al. (2002) introduced the *enhanced vegetation index* (EVI) which is calculated as:

$$EVI = G \frac{\rho_{NIR} - \rho_{red}}{\rho_{NIR} + C_1 * \rho_{red} - C_2 * \rho_{blue} + L} \quad (10)$$

where G is a gain factor, C_1 and C_2 are the coefficients of the aerosol resistance term and ρ_{blue} is the reflectance in the blue band. The G, C_1 and C_2 have been set to be 2.5, 6 and 7.5, respectively (Huete et al. 2002). The authors also used a value of L equal to 1. The C_1 and C_2 terms use the blue band to correct for aerosol influences in the red band. The EVI was developed to optimize the vegetation signal by improving the sensitivity in high biomass conditions, taking out the background effects (leaf litter or soil) and by reducing the effects

of the atmosphere. EVI has been mostly used for images of the Moderate-Resolution Imaging Spectroradiometer (MODIS) sensor for monitoring vegetation.

The rationale behind the vegetation indices is that increasing vegetation LAI increases reflectance in the NIR due to a low leaf absorption in this spectral region, while in the red region a decrease occurs. It has been shown that most of the indices saturate for LAIs above around 3 (Tucker, 1979). However, the shape of the curve of fAPAR (the fraction of absorbed PAR) is the same as NDVI versus LAI. Sellers (1987) showed that the SRVI has a nearly linear relationship to fAPAR. Myneni et al. (1992) showed a nearly linear relationship between fAPAR and NDVI and a simple linear model relating fAPAR to top of canopy NDVI has been proposed (Myneni & Williams, 1994). Global datasets of time series of NDVI and EVI are available (e.g. Lhermitte et al., 2011), which make them highly attractive for monitoring grasslands over large areas and for estimating canopy conditions.

2.4.2 Canopy radiative transfer model inversion

Canopy radiative transfer models have been developed to simulate bidirectional reflectance factor of vegetation canopies (BRF). One simulated BRF ($BRF_j(S)$) can be represented by a function or algorithm, f , of subsystem characteristics (a_j, b_j, c_j, d_j, e_j) (Goel & Strebel, 1983, Goel, 1988):

$$BRF_j(S) = f(a_j, b_j, c_j, d_j, e_j) \quad (11)$$

where a_j, b_j, c_j, d_j and e_j define the source, the atmosphere, the vegetation, the soil and the sensor subsystems, respectively. The source is characterized by the solar zenith and azimuth angles and the total flux intensity (normalized to one), the atmosphere is characterized by the direct plus diffuse radiation, the canopy is characterized by the leaf reflectance (ρ_p) and transmittance (τ_p), LAI, LAD and the leaf spatial distribution parameter (λ_0), the soil is characterized by the soil reflectance (ρ_s) and the sensor is characterized by the view zenith (VZA) and view azimuth angles.

The inversion process consists of deriving a function or algorithm, g , that will yield the set of canopy parameters $\{c_j\}$, as a function of the observed canopy BRF ($BRF(O)$) and the other subsystem characteristics (Goel & Strebel, 1983):

$$\{c_j\} = g(BRF_j(O), a_j, b_j, d_j, e_j) \quad (12)$$

Soil reflectance $\{d_j\}$ may also be derived through the inversion process along with the vegetation canopy parameters. The numerical inversion of a canopy radiative transfer model involves the minimization of differences between a set of simulated and observed BRF values acquired under different illumination/viewing geometries. Canopy parameter values that give the lowest difference between $BRF(S)$ and $BRF(O)$ are the estimated canopy values.

One limitation of the inversion process is that the number of observed values must be at least equal to the number of canopy parameters to be retrieved. This makes the process difficult for satellite image applications as most of the sensors collect single illumination/viewing geometry. This also limits the number of estimated parameters,

which in most applications is the LAI. The validity of the inversion process has been validated for estimating canopy parameters of grasses using field radiometry observations (Privette et al., 1996). They have demonstrated the feasibility of estimating LAI, LAD, leaf reflectance and transmittance, total canopy *albedo* (the reflected radiation integrated over the hemisphere and the solar spectrum) and the fraction of absorbed photosynthetically active radiation. Inversion has also been used to estimate LAI and leaf chlorophyll for grassland (Darvishzadeh et al., 2008) and for sugar beet canopies (Jacquemoud et al., 1995) using spectroradiometer data and the PROSAIL model developed by Jacquemoud & Baret (1990).

3. Canopy structure and radiation flux interactions

In this section we initially present a brief description of the morphological characteristics of some forage grasses that are used for dairy and meat production in pasture-based systems, address some features relative to LAI and radiation interception measurements, and finally, we use a stoloniferous (*Cynodon* spp.) and a tufted (*Pennisetum purpureum*) grass for discussing experimental work about the extinction coefficient, leaf and stem area development and canopy angular distributions.

3.1 Typical growth habits of tropical forage grasses

In terms of tropical perennial forage grasses, two main morphogenetic groups with typical growth habits are usually recognized: i) tussock grasses, which are grasses that produce tillers, and have an erect and clumped growth form; and ii) creeping grasses, spreading by stolons, rhizomes or both (Skerman & Riveros 1989, Cruz & Boval, 2000, Van de Wouw et al., 2009). The first group includes tufted species as *Pennisetum purpureum*, *Panicum maximum*, *Andropogon gayanus*, *Hyparrhenia rufa* and *Brachiaria brizantha* while the examples of the second group are: *Brachiaria humidicola*, *Brachiaria mutica*, *Digitaria decumbens* and *Cynodon nlemfuensis* (Figure 2). Of course there are also species which can be defined as morphological intermediates, examples are: *Dichanthium aristatum*, *Dichanthium annulatum*, *Bothriochloa pertusa* and *Digitaria decumbens* (Cruz & Boval, 2000), and less common are: *Brachiaria* (Syn. *Urochloa*) *decumbens*. As pointed out by Cruz & Boval (2000) these morphological intermediates have the capacity to develop into stolons when growing as isolated plants, but in dense stands, most of the stems do not reach the ground but grow laterally at the top of the canopy.

3.2 Measurement of solar radiation interception

The instantaneous or daily integrated PAR absorbed at each level by a grass canopy (APAR) is the main factor determining the rate of carbon assimilation of individual leaves (Nobel et al., 1993). Therefore it is an important input for canopy photosynthesis models, once at the ecosystem level, leaf canopy is the unit of photosynthesis (Nouvellon et al., 2000, Hikosaka, 2005). Conceptually APAR, as an expression of the energy flux available, is the result of the difference between the net radiation above the canopy and the net radiation below the canopy (Norman & Arkebauer, 1991). It is calculated as:

$$\text{APAR} = (E_{i\lambda} - E_{rc\lambda}) - (E_{t\lambda} - E_{rs\lambda}) \quad (13)$$

where E_{rc} and E_{rs} are the symbols for radiation reflected by the canopy and the soil surfaces, respectively, and $\lambda = 400\text{-}700\text{ nm}$. For most purposes APAR is approximated by a more easily estimable quantity, the intercepted PAR (IPAR) which expresses a difference between incoming PAR (E_i) and the radiation transmitted to the bottom of the canopy (E_t).

$$\text{IPAR} = E_i - E_t \tag{14}$$

One measure of light interception efficiency is given by the relationship between IPAR and the total incident PAR at the top of the canopy, named fractional IPAR (fIPAR).

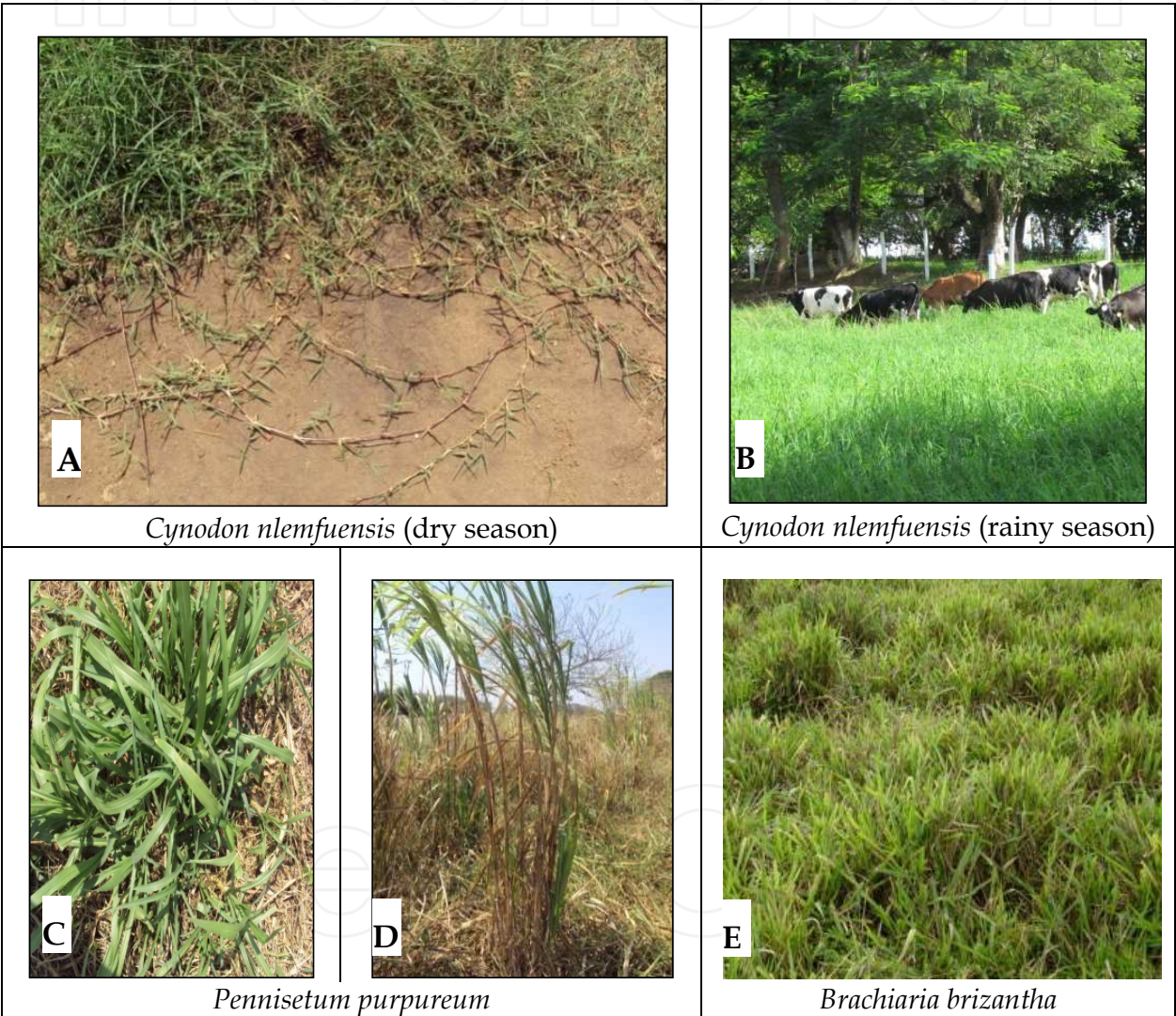


Fig. 2. Some tropical perennial forage grasses. A) Porto Rico Stargrass (*Cynodon nlemfuensis*), showing the stoloniferous growth habit at the edge of a experimental plot (September 2011, end of dry season). B) Dairy heifers grazing on the same pasture, during the rainy season (January 2011). C) Regrowth of napier grass (*Pennisetum purpureum*) sixty days after cutting; D) with subsequent growth, napier grass shows a like-cane growth habit, with erect culms. E) A marandu palisadegrass (*Brachiaria brizantha* cv. Marandu) sward in a dairy farm in Southern Minas Gerais State. (Photographs: courtesy by Dr. Sérgio T. Camargo Filho, Researcher of PESAGRO, Rio de Janeiro).

Soil nitrogen (N) has a strong effect on plant growth. Many studies, worldwide have shown that crop N uptake is co-regulated by both soil N supply and biomass accumulation processes (Fernandes & Rossiello, 1995; Hikosaka, 2005; Lemaire et al., 2007). When water supply is non-limiting, both carbon and nitrogen capture and use processes are closely linked with one another by the development of leaf area and the pattern of intercepted radiation (Lemaire et al., 2007; Giunta et al., 2009), since about half of leaf nitrogen is invested in photosynthetic proteins (Ghannoum et al., 2005; Hikosaka, 2005). Because of these interrelationships, we also consider the roles of N nutrition in the processes of interception and use of solar radiation by forage grasses.

In Figure 3, are presented the data related to fractional PAR intercepted by swards of Tifton 85 bermudagrass (*Cynodon* spp.), during field measurements to evaluate the effects of nitrogen fertilization on several physiological and morphological traits of the grass. Data were selected due to its simplicity of expression, as they show clearly that an increase in availability of N causes a temporal acceleration of the fractional IPAR by the sward, according to a logistic pattern. In practical terms we can say that N accelerates the canopy closure. Thus, at the high level of application of N, a fractional IPAR value of 0.9 was rapidly obtained, about three weeks after the beginning of the rest period. In contrast, in the same period, the control treatment did not surpass the level of 0.5 fIPAR.

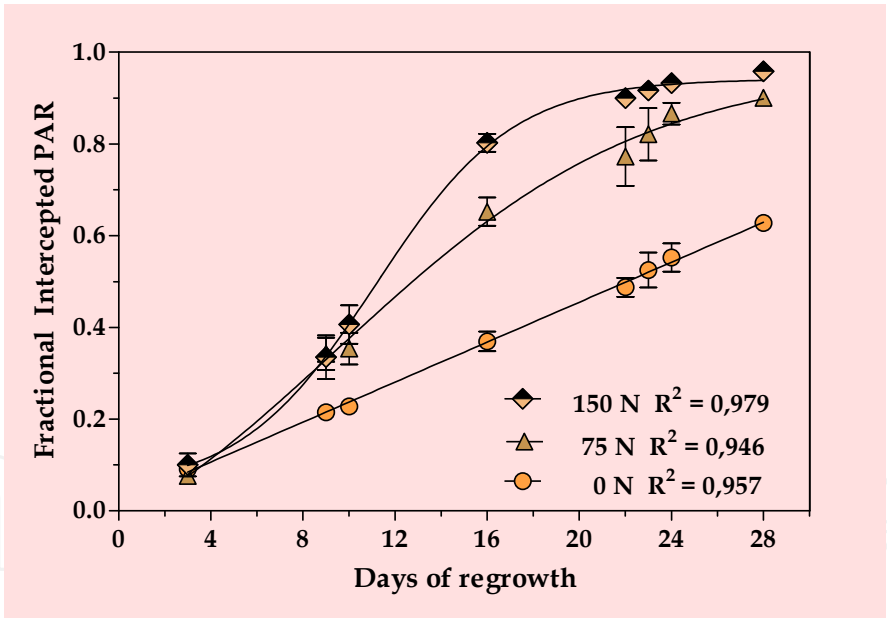


Fig. 3. Temporal variations of instantaneous fractional PAR interception values by Tifton 85 bermudagrass canopies under three rates of nitrogen fertilization. Experimental plots (4m x 4 m) were established in July 2008 on a Typic Fragiudult soil in Seropédica, RJ, Brazil. Several measurements were performed between November 30th and December 28th (rainy season) using optical instrumentation. After twenty-eight days, when the 150-N plots reached a level of 0.95 fIPAR (mean of four replicates) the regrowth cycle was finished by cutting. Environmental conditions during the period were as follows: mean solar radiation: 15.9 MJ m⁻² day⁻¹, mean air temperature: 25.4° C and total rainfall: 222.5 mm (E. Barbieri Junior & R. Rossiello, unpublished data).

These results can be attributed to the effects of N on the morphogenetic traits responsible for the structural features in this type of pasture (Cruz & Boval, 2000), where axillary meristems develop as horizontal stolons (Figure 2A) under high levels of sunlight and good water supply. Particularly, in this case, nitrogen stimulated significantly ($p \leq 0.05$) canopy height growth rates, tiller population density and leaf area development (data not shown).

Some issues related to measurement procedures are pertinent. Photosynthetically active radiation was measured at the top of the sward canopy using a single quantum sensor (LI-191SA) while at the bottom the transmitted PAR was recorded with a LI-191 SA line quantum sensor connected to a LI-250A light meter (LI-COR Inc., Nebraska, USA). The sensor was inserted at the soil surface level regardless how much of dead material was present. This was possible due to young age of this hybrid bermudagrass with a small amount of dead material accumulated at the base. However, older perennial pastures may have sizeable amounts of dead phytomass accumulated on the bottom of the canopy (Le Roux et al., 1997, Guenni et al., 2005, Sbrizzia & Silva, 2008). In stoloniferous species, after 4 or 5 weeks of growth under non-N-limiting conditions, the loss of leaf biomass as a consequence of changes in allocation patterns can account for half of the leaf tissues produced (Cruz & Boval, 2000). In these situations an appropriate evaluation of fIPAR may be a substantial problem. As an example, let us consider data on vertical light distribution in the pasture of Porto Rico Stargrass showed in Figure 2A. Measurements were taken under clear sky using optical equipment described above (Figure 4). Results showed that canopy light interception at 12.5 cm and at sensor level heights were 0.873 and 0.986 respectively, i.e. dead phytomass layer was responsible for about 11% of fIPAR (Figure 4A). On the other hand, in a plot adjacent, vegetated by Swazi grass (*Digitaria swazilandensis* Stent), the same variables have values of 0.930 and 0.988 respectively (profile not shown) reflecting morphological differences among the structural components of the two pastures. As noted previously by many researchers, when measuring grass light interception with optical sensors, it is nearly impossible to position the sensor under the grass canopy without disturbing it (Russell et al., 1989). One possible way of avoiding this problem, when disturbance is very apparent (Figure 4B), is to use a single sensor screwed to a transparent ruler graduated (Figure 4C), it is a solution more functional at plot than at field scale. Under field conditions, it may be more interesting to consider the bottom of the sward canopy a given "cut level" above the horizon of standing dead material, knowing however that the amounts of dead material accumulated are seasonally determined.

3.3 Leaf area index, extinction coefficient and angular distribution of canopy elements

Interception of PAR is modified by canopy architecture as represented by the extinction coefficient, k (Bréda, 2003, Zhou et al., 2003). For simulation purposes in canopy photosynthesis and radiation interception models, a fixed value for k is sometimes assigned (Thornley, 2002). However, research with real canopies has shown that this coefficient varies seasonally, in line with changes in traits such as leaf angle, canopy height or LAI (Bréda, 2003, Polley et al., 2011). A fixed value of k may be appropriate for estimating values of ceiling LAIs, i.e. when fIPAR is around 0.90 and the crop growth rate is near its maximum. However, during the previous vegetative growth, in several instances, it has been shown that k changes as sward architecture changes. Nouvellon et al. (2000), working with shortgrass ecosystems in northwestern Mexico found that the k value for diffuse and global

radiation decreased as LAI sward increased. We found the same trend in canopies of Tifton 85 bermudagrass modified by nitrogen fertilization. In our study, decreases in k_{PAR} with sward height seemed to fit a linear pattern (Figure 5). In this case, sward height is a direct surrogate for herbage biomass or foliage density, structural properties with which it is highly correlated (Oliveira et al., 2010).

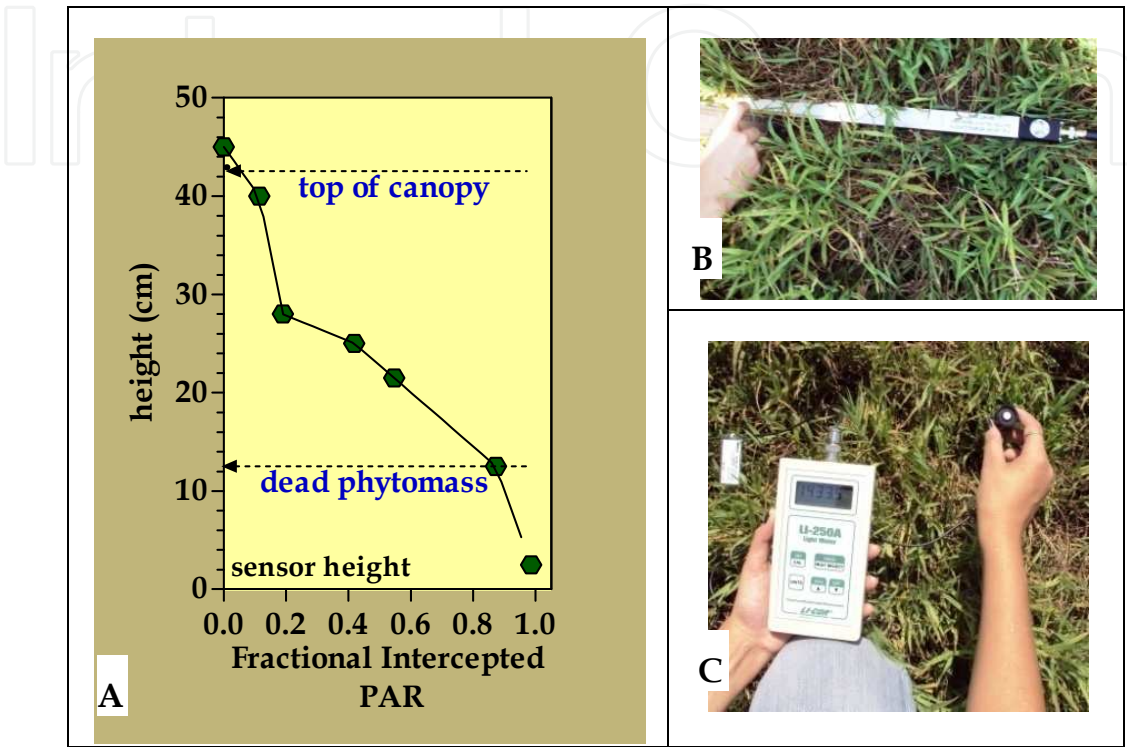


Fig. 4. Vertical light distribution in canopies of two stoloniferous species. A) Profile of a Porto Rico Stargrass sward (same as Figure 2A). At the site, mean heights of canopy and dead phytomass were 43 cm and 12.5 cm respectively. Sensor height is 2.5 cm and therefore, when facing upward, this is the location of its sensitive surface nearest ground surface. B) Plot of Swazi grass (*Digitaria swazilandensis* Stent) near the anterior. The proper deployment of the line quantum sensor is impeded by a dense layer of dead material so that its sensitive surface lies suspended at 7.5 cm from the soil surface. C) A better option may be to move a simple sensor through a vertical length of the canopy (Mean height: 29 cm). Measurements were taken on day 21st of September 2011 at PESAGRO Experimental Dairy Farm, Seropédica, RJ, Brazil, at the time corresponding to SZA between 24.8° and 28.0°.

Preliminarily we must recognize that k_{PAR} data as shown in Figure 5 are, to some degree, oversized. This fact is a result of using an optical approach for the measurement of intercepted PAR. The instrumentation used in this method does not discriminate between leaves and stems, or among green, senescent or dead leaf blades (Asner et al., 2003, Bréda, 2003). Overestimation arises because k values are calculated with the transmission values of the whole standing foliage, but with LAI values that includes only green leaf blades, which is the so-called “true LAI” (He et al., 2007). However the magnitude of this overestimation is a matter of debate because it is species- specific (Bréda, 2003, Guenni et al., 2005, He et al.,

2007), and in our case it is assumed that it is distributed equally among the treatments since the canopy leaf to stem ratio was almost invariant (Figure 5). Given this, the data indicate that under nitrogen influence, there is a structural change in the canopy towards a more erectophile condition.

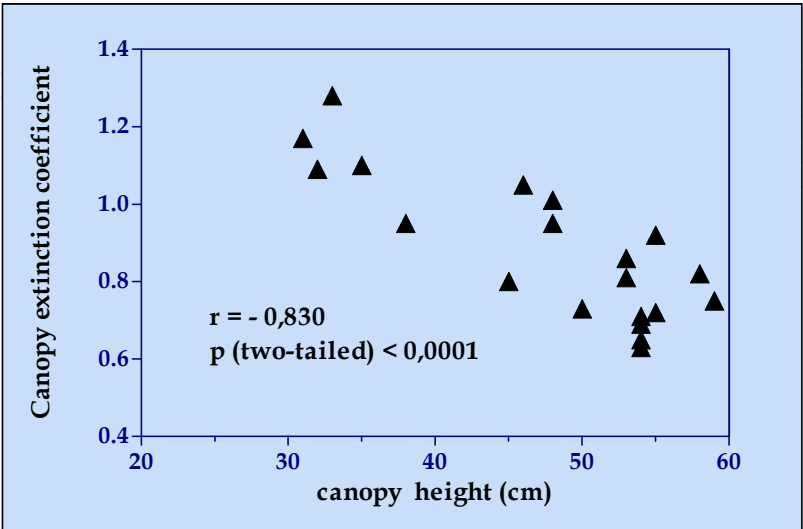


Fig. 5. Canopy heights of Tifton 85 bermudagrass related to corresponding extinction coefficients (k_{PAR}) values, after a regrowth period of 35 days (From January 25th to March 1st 2007). Variations in these traits were induced by nitrogen fertilization (0, 75,150,227 and 300 kg N-urea/ha). Concurrent values of Green Leaf Area Index ranged from 0.78 to 4.19. Mean leafiness (leaf blade: stem ratio) was 1.09 ± 0.05 and did not vary significantly ($p > 0.05$) among applied N doses (A.P. Oliveira & R. Rossiello, unpublished data).

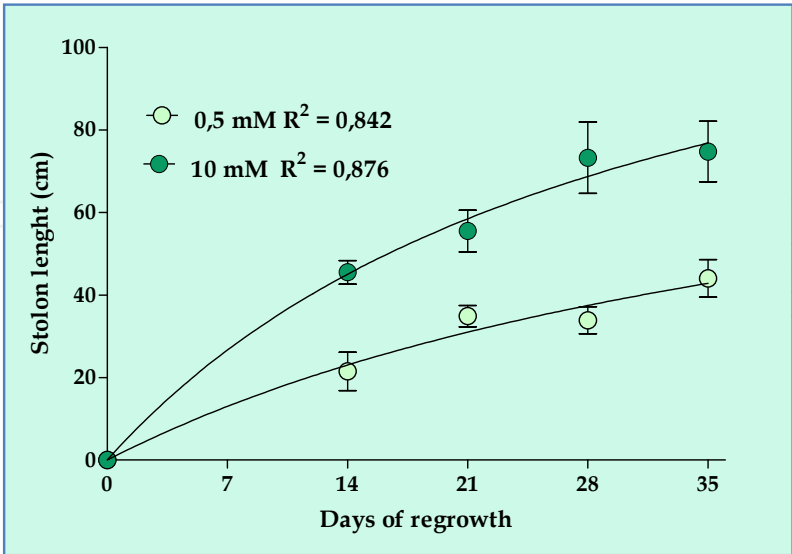


Fig. 6. Maximum stolon length of clonal propagules of Tifton 85 bermudagrass grown in Hoagland solution culture, in response to N levels (0.5 or 10 mM) and days of regrowth in a controlled growth environment . Photosynthetic photon flux density: $450 \mu\text{mol photon m}^{-2} \text{ s}^{-1}$, air temperature (day/night): $30/24^\circ \text{C}$, photoperiod: 12 h. (R. Rossiello, unpublished data).

As the theory predicts we can suppose that this result is due to changes in LAD, but how the changes take place is unclear. A possible interpretation is that by influencing canopy development, nitrogen modifies the light spectrum within the canopy with consequences for the stolon differentiation (Cruz & Boval, 2000). In *Cynodon* species or cultivars, large variation in length and number of stolons might be due to the very plastic response of stolons to light intensity and nutrient availability (Van de Wouw et al., 2009). Willemoes et al. (1987) observed that bermudagrass stolons irradiated with red light showed an upward curvature and an increase in leaf and internode lengths in comparison with those grown in darkness or under red plus far red radiant flux. Thus even in the low levels of photosynthetic irradiance existing in the middle of Tifton 85 canopies, high N availability in the growth medium could increase stolon elongation process, as can be inferred from results obtained in controlled environmental conditions (Figure 6).

In fact, light fluxes fluctuating deeper in the canopy, with variables red/far red ratios, in the presence of a growth substrate rich in N, could form the basis of the canopy response showed in Figure 5. Of course, we can also suppose that this type of response could be a consequence of absence of grazing pressure on shoot morphology. However, in a very different context, Pinto et al. (1999) working with Tifton-85 swards being continuously grazed by sheep found that taller swards (more lenient grazing) had the lowest senescence rates and suggested that changes in sward structure with increasing sward height could be promoting changes in the canopy light environment. Clearly this is an area that deserves more ecophysiological research.

Season has a strong influence on canopy structural properties due to the seasonal course of solar elevation and the associated changes in ratios of diffuse to direct solar beam. Kubota et al. (1994) observed a large structural change of napier grass canopy with growth. Young shoots of the cultivar Merkeron were transplanted in a field and grown for 102 days. During this growth period LAI increased from 0.7 to 15.4 while k decreased gradually from 1.1 to 0.38 due to elongation and erection of stems (large increase in the frequency of stalks with angles of 80-90° relative to the soil surface, see Figure 1B). These results indicate that in this grass, changes from a planophile to an erectophile growth pattern (see Figures 2C-D) are accomplished by correlative variations in SAD. This type of modification protects lower leaves from heavy shading, allowing the canopy to approximate an optimum LAI throughout the growth period (Kubota et al., 1994). Besides this, a long duration of vegetative growth are regarded as the main causes of high productivity of this species, with aboveground dry mass yields of 60 tons/ha/year (Morais et al., 2009). Zhou et al. (2003) working with sugarcane (*Saccharum* spp.) cultivars in Zimbabwe, Africa, obtained different results. They found that the k_{PAR} values of four cultivars (calculated by solving for k in the light extinction expression, as in Figure 5) increased (although not significantly, $p > 0.05$) with increasing crop age, with a mean from 0.47 at 87 days to 0.64 at 116 days after planting. Additionally, it was observed that high stalk population cultivars intercepted more PAR than low stalk population cultivars because they had more intercepting leaf surfaces, but leaf size seemed less important than tiller population to explain differential patterns of PAR interception among cultivars. However, no information about possible differences in stalk angular distribution was given. In still other situations, there may be compensations between LAD and SAD during the growing season, so that the net effect of shifts in canopy angular distribution on light interception is decreased. This was the case in the above work

of Nouvellon et al. (2000) who observed that early in the season, LAD was highly erectophile and shifted towards a less erectophile condition during the seasonal growth. However, this trend was compensated by a higher contribution of the highly erectophile stems (LAD↓ and SAD↑) to the total plant area index in the later stages of plant development. These findings suggest that, although in most cases the leaf angular distribution is the predominant factor in solar radiation interception; in some situations the role of steam angular distribution cannot be ignored.

There are few works dealing with values of LAI and light interception of tropical and subtropical grasses under conditions of cutting or grazing. In grazed pastures, leaf tissues are subjected to discrete defoliation events, the frequency and intensity of which greatly affect the physiology of plants and therefore the rate at which new leaf tissues are produced (Lemaire & Agnusdei, 2000). As a general rule, recommendations for grazing management are made in order to preserve a residual LAI suitable for the plants to continue growing thus maintaining the persistence of the herbage resource. In this context, the height of post-grazing residue is one of the determining factors of the regrowth rates in tropical pasture grasses, especially for tussock grasses as *Pennisetum purpureum* (Zewdu et al., 2003). In this species the dynamics of tillering in terms of tiller classes also influences growth rates and herbage accumulation (Skerman & Riveros, 1989). Carvalho et al. (2007) studied the effect of these two variables on the seasonal patterns of leaf area development and light interception, in an experiment performed at an experimental field of Embrapa in Coronel Pacheco, MG, Brazil (21° 33' S, 43°06' W, 410 m).Two post-grazing residues (50 and100 cm) and two tiller classes (basal and aerial) were combined in a split-plot arrangement, from October 2002 to April 2003. Selected results of this work are shown in Figure 7.

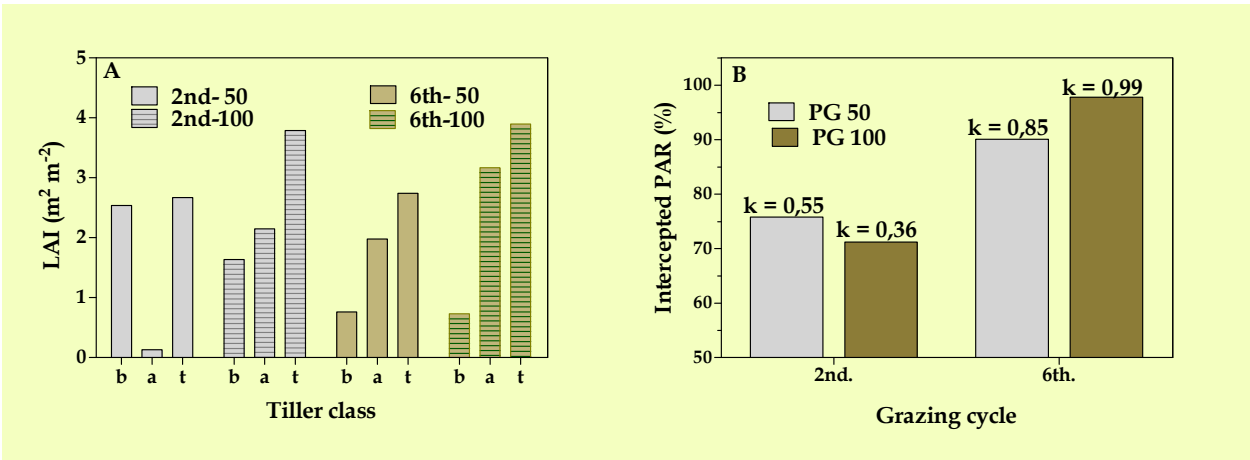


Fig. 7. Effects of post-grazing residue (50 and 100 cm) and tiller class on leaf area index (LAI) and PAR interception of napier grass swards during two grazing cycles. A) Leaf area index of basal (b), aerial (a) and total (t: basal + aerial) tillers affected by sward height post-grazing residue and grazing cycle. B) Canopy PAR interception values, evaluated in pre-grazing conditions, in response to the same variables. Number at the top indicates the value of extinction coefficient (*k*). LAI was determined destructively, according to: LAI = leaf area.tiller⁻¹ × tiller number.m⁻². IPAR was measured using LI-COR optical sensors. Grazing cycles: second, from November 3th to December 6th 2002; sixth, from March 15th to April 17th 2003. (Adapted from Carvalho et al., 2007).

During the spring there was a larger appearance of basal tillers in swards managed at 50 cm post-grazing residue. Conversely, population densities of aerial tillers were predominant in the summer months. Interestingly, within each residue height, LAIs values were practically the same in the second and sixth grazing cycles, with different contributions of both tiller types (Figure 7A). However, LAI variations and PAR interception were not strongly related throughout the experimental period. The progressive increase in k values from 2nd to 6th cycle indicates that over the grazing cycles the foliage acquired a more planophile arrangement linked to a seasonal change in plant architecture. This shift was mediated by the afore-mentioned proliferation of aerial tillers which have a lower insertion angle than basal tillers and make up a flatter canopy (Carvalho et al., 2007). The marked dominance of aerial tillers in the last grazing cycle was apparently responsible for a greater PAR interception in the pre-grazing condition especially in pastures managed with 100 cm of residue (Figure 7B). However the authors do not exclude the contribution of dead material in this response. Qualitatively similar results were obtained by Giacomini et al. (2009) working with marandu palisadegrass (*Brachiaria brizantha* cv. Marandu, Figure 4E) subjected to intermittent stocking.

4. Radiation use efficiency

Monteith (1972) showed that phytomass production under tropical climate conditions is correlated with the amount of photosynthetically active radiation (PAR) absorbed by plants. This finding provides the basis for deriving the concept of ecosystem gross primary productivity (GPP). Ecosystem GPP may be calculated using algorithms that employ the light-use efficiency (LUE) concept (Polley et al., 2011). LUE (ϵ) is a conversion factor or the ratio of GPP to APAR (Equation 13). Following this concept, we have:

$$\text{GPP} = \text{APAR} \times \epsilon_{\text{PAR}} = \text{PAR} \times f_{\text{APAR}} \times \epsilon_{\text{PAR}} \quad (15)$$

where f_{APAR} is the fraction of PAR that is absorbed by the grass canopy. From this identity, we can infer that green or dry biomass could be increased when radiation absorption or use efficiency, or both, are maximized. However, Norman & Arkebauer (1991) considered two meanings for the term “use efficiency”: *i*) mass of CO₂ fixed per unit of absorbed photosynthetically active radiation, or *photosynthetic light-use efficiency* and *ii*) mass of dry matter (DM) produced per unit of absorbed photosynthetically active radiation or *dry matter light efficiency* which is the same as Equation 15. As noted by these authors, the second definition is more problematic as it involves both maintenance and growth respiration terms, which may not depend on light directly. Despite this objection, this agronomic definition is the most frequently cited in radiation use research, where IPAR can replace APAR (Norman & Arkebauer, 1991). According to Albrizio & Steduto (2005) for a given species and environment, RUE is approximately a constant value during the growth season, provided that: *i*) respiration is proportional to photosynthesis; *ii*) photosynthesis response to irradiance is essentially linear at the canopy scale and *iii*) no substantial change in the chemical composition of biomass occurs during the growth cycle considered. Under non-limiting water and nutrient conditions, all of these conditions can be met for tropical forage grasses, however, to date there are few available data. Guenni et al. (2005) reported RUE values for five *Brachiaria* species that ranged (not significantly) from 1.3 to 1.7 g DM (MJ IPAR)⁻¹ for *B. brizantha* and *B. humidicola*, respectively.

5. Conclusions

Multi-functionality approach recognizes that grasslands have to be considered not only as a means for providing animal products for increasing human population. Also, other additional ecosystem functions as enhancement of carbon sequestration or mitigation of greenhouse gas emissions should be considered by farmers as a way of capitalizing new opportunities to diversify the forage-livestock system (Lemaire, 2007, Sanderson et al., 2007). However returning to the first page of this chapter we remember that degradation processes in tropical grassland are advancing over wide areas through overgrazing on poor soils. So it seems that recuperation and multi-functionality concepts in pasture ecosystems will transit a long way together. We state the central role that the leaf canopy structure, expressed as leaf area index, plays in terms of intercepting solar radiation. Despite this, there are very few studies comparing different alternatives of estimating LAI in forage plants, particularly those of tropical climate. There are several possibilities to apply technologies already available in the generation of new methods. Some of these include: *i*) use of remotely sensed data for monitoring canopy parameters (vegetation indices as NDVI, SAVI and others), *ii*) measurements of foliage cover through digital color photographs taken vertically above the plant canopy using a stationary camera stand (Rotz et al., 2008), *iii*) a more intensive and creative use of the gap fraction methods including examination of hemispherical photographs for estimates of foliage angular distribution and canopy leaf area. Regarding this last information, the orientation of foliage elements (stems and leaves) is an important piece of information for describing light penetration in canopies especially for tussock grasses.

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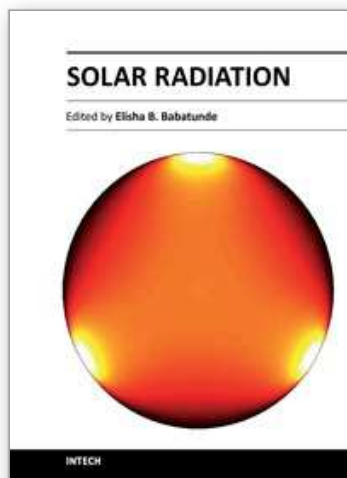
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