NARDI FUNDULEA, ROMANIA
www.incda-fundulea.ro
ROMANIAN AGRICULTURAL RESEARCH, NO. 35, 2018
Print ISSN 1222–4227; Online ISSN 2067–5720

ON THE ASSESSMENT OF LIGHT USE EFFICIENCY IN ALFALFA (*MEDICAGO SATIVA* L.) IN THE ECO-CLIMATIC CONDITIONS OF TÂRGOVIŞTE PIEDMONT PLAIN

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ABSTRACT

The overall objective of this research was to study the light use efficiency (LUE) of alfalfa (*Medicago sativa* L.) in the eco-climatic conditions of Târgovişte Piedmont Plain. A field experiment with two Romanian varieties (Roxana and Mihaela) developed by NARDI Fundulea was conducted in pure stand between 2012 and 2014, using a Latin rectangle design with four replicates and three cutting cycles per year. Dry matter accumulation, leaf parameters and light capture characteristics did not show significant differences between the two tested varieties (p>0.05) in non-irrigated conditions. The maximum LAI at the first cutting was 5.1 for Roxana, and 5.3 for Mihaela. The ELADP varied between 1.47 and 2.36, while light extinction coefficient (k) had a synthetic average of 0.8. The energy transmitted to the canopy ranged between 7.4 and 22.3 μmol m^{-2} s^{-1} on average. The coefficient of absorption varied between 0.75 and 0.83 depending on variety and experimental year. LUE of alfalfa ranged between 0.23 and 0.27 g $moles^{-1}$ m^{-2} day^{-1}. The resulted elements characterizing the light interception and absorption processes in alfalfa, which were determined dynamically during the growth seasons, are useful for the parameterisation and utilization in dedicated crop growth models.

Key words: photosynthetically active radiation, photosynthetic photon flux density, light extinction coefficient, leaf area index, ecophysiological response.

INTRODUCTION

Alfalfa (*Medicago sativa* L.) or lucerne is one of the most important fodder crops in temperate climate regions, presenting a superior ecological plasticity due to its adaptability to various ecological, climatic and soil conditions. The widespread cropping of alfalfa is explained by its increased productivity, forage quality, and valuable biological characteristics. Alfalfa can produce under normal conditions yields of 7-8 t ha^{-1} Dry Matter (DM) in non-irrigated conditions, respectively 12-15 t ha^{-1} DM when irrigation is applied (Moga et al., 1996).

Alfalfa showed an increased digestibility of green, hay or silage fodder compared to other cultivated legumes (e.g., red clover, Bird's-foot-trefoil) in temperate regions (Cassida et al., 2000), but lower than white clover (Buxton et al., 1985). The feeding value of alfalfa varies between 0.6 and 0.7 kg Nutritive Units/kg DM, depending on the harvesting time (Moga and Schitea, 2005; Muntianu et al., 2012). Aerial dry matter accumulation (ADM) and qualitative parameters of forage are directly correlated to the amount of photosynthetically active radiation intercepted (PARi) by the canopy of species (Monteith, 1977). Interception of light in homogeneous canopies is influenced by the leaf area index (LAI), the leaf area positioning (canopy layers) and absorption characteristics of the species (Campbell and van Evert, 1994). Higher position of leaf layers determines increased rates of radiation absorption and reflectance compared to those located below them (Dunea and Dinca, 2015). The light absorption characteristics of species depend on optical properties, thickness and goniometric distribution of leaves (McCree, 1972). The leaf area distribution determines the amount of radiation absorbed per canopy unit of leaf area. McCree (1972) showed that

Received 18 January 2017; accepted 15 January 2018. First Online: January, 2018. DII 2067-5720 RAR 2018-4.

planophile leaf species (e.g., legumes) capture light more efficiently than erectophile canopies (e.g., perennial grasses). However, the canopy photosynthetic efficiency will be significantly higher in erectophile than in planophile canopies at similar absorption rates of photosynthetic photon flux densities (PPFD) – quantum flux density. It is the number of photons in the 0.4-0.7 µm waveband incident per unit of time on a unit of surface (Varlet-Grancher et al., 1989). In energetic terms of PAR, Thiébeau et al. (2011) found for alfalfa that radiation use efficiency (RUE) for aboveground dry matter was equal to 1.72 g DM MJ^{-1} irrespective of sowing date (spring or summer).

The RUE of seedling crops always exceeded those of regrowth crops present at the same period. Seedling crops of alfalfa were slower to establish their LAI than regrowths, but used cumulative intercepted radiation as efficiently as the latter. RUE is a key indicator of biological efficiency of a species regarding the conversion of light in dry matter (ε_b). Allirand (1998) used the following equations to estimate the ε_b of alfalfa (*d* - day):

$$PARi(d) = PAR(d) \cdot 0.97 \cdot$$
$$\cdot [1 - \exp(-0.88 \cdot LAI(d))]$$
$$DM(d) = \varepsilon_b \times \sum_{D}^{d} PARi(d)$$
$$\varepsilon_b = 1.76 \ g \ DM \cdot MJ^{-1}$$

Leaf area data are essential to predict crop yields and evaluate modifications in canopy structure due to intrinsic genetic factors or climate change and pollution impact. Schitea et al. (2007) found LAI values ranging between 5.3 and 5.6 in five Romanian varieties of alfalfa. Gosse et al. (1986) reported a synthetic value of 0.88 for light extinction coefficient (*k*) for alfalfa canopies. The reflectance factor was approximated at 0.97 (Justes et al., 2002). In a temperate environment, spring re-growth cycles had a mean individual leaf area of 170 mm^2 compared with 400 mm^2 for summer re-growth cycles (Brown et al., 2005).

In this context, the rationale of the study was to parameterize the alfalfa canopy and related light use behaviour for the specific eco-climatic conditions of Târgovişte Piedmont Plain, Romania. In this area, the farmers prefer alfalfa for cropping because of its robustness in the detriment of red clover, which is more suitable in such eco-climatic conditions due to its biological characteristics, but concomitantly is a more pretentious crop. The paper presents the relationships between the light use efficiency and aerial components i.e., leaf area index, leaf area distribution, canopy height of alfalfa that are responsible for the yield formation, recorded in the first two years of cropping i.e., 2012 and 2013. We used the quantic fluxes (moles $m^{-2}s^{-1}$) intercepted by the canopies of two Romanian varieties (Roxana and Mihaela), which were developed by NARDI Fundulea (Schitea, 2010), sown in pure stand. The resulted variables are important to improve the simulation performed using dedicated crop growth models (Robertson et al., 2002; Dunea et al., 2016).

MATERIAL AND METHODS

Experiments were carried out in Târgovişte Piedmont Plain, Romania (Figure 1) at Dobra village (N44°46¹.905, E25°43¹.045, 179-m altitude) between 2012 and 2014. The soil was pseudogleic brown alluvial. Two Romanian alfalfa cultivars i.e., Roxana and Mihaela were selected to be used in a Latin rectangle design with four replicates. NARDI Fundulea developed both varieties with very valuable biological traits (Schitea, 2010). These synthetic cultivars that were obtained from the recombination of foreign and Romanian germplasm are characterized by rapid spring growth, faster regrowth after cutting, good resistance to common diseases occurring in Romania, and improved winter hardiness (Schitea et al., 2007). The plots were sown in pure stand in March 22, 2012. The plants were given nitrogen fertilizer in all experimental variants at one rate (25 kg N ha^{-1}) to avoid nutrient limiting growth. Irrigation was not applied to comply with the common cropping practices used by farmers.

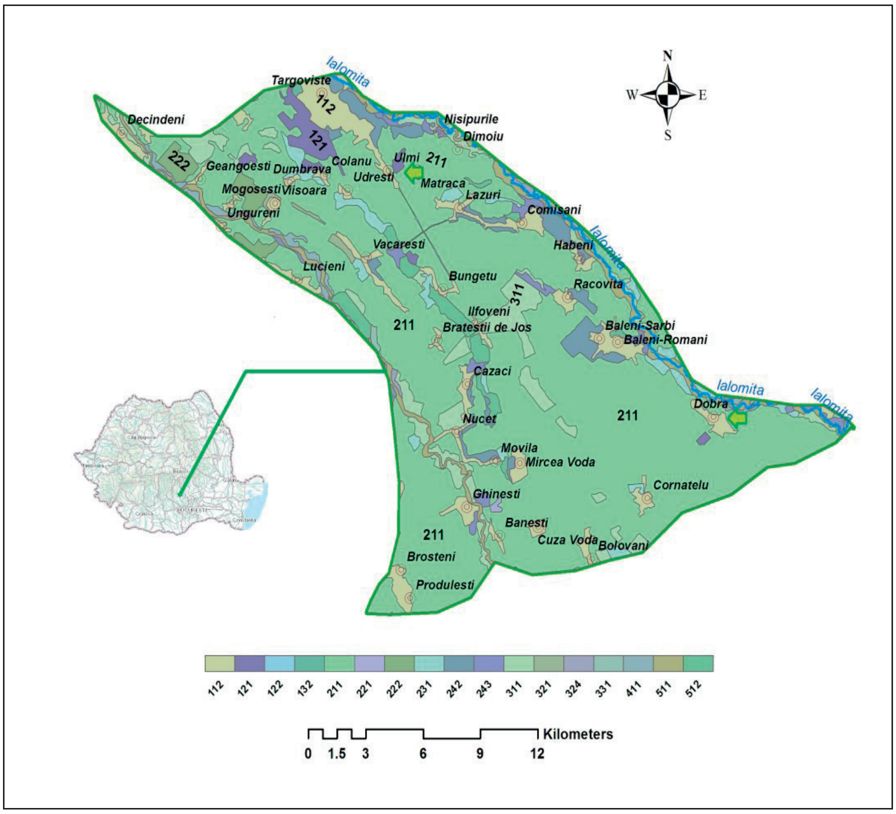

Figure 1. Location of the experiments – Dobra Village; map of Târgovişte Piedmont Plain showing the CORINE land use/land cover units (e.g., 211 – agricultural crops; 222 – orchards; 311 – deciduous forests; 112 and 121 – urban land use classes) – map was obtained using ESRI ArcGIS features (Dunea et al., 2016)

Three forage cuttings were performed each year i.e. 1st cutting: at the beginning of flowering stage; 2nd: + 7 weeks from the 1st cut; 3rd cutting: + 6 weeks after 2nd cutting.

Bulk harvests were conducted using a quadrate of 50 × 50 cm in two points of each replicate for taking samples.

Alfalfa laminae were measured with a leaf-area meter. Harvested material was dried at 70 ºC for 24 hours, and weighed to estimate dry matter accumulation.

The monthly average temperature recorded between March 2012 and December 2013 was 10.8 °C. Figure 2 presents the evolution of temperature at the experimental site. The rainfall regime was close to the normal of the region for both studied growth seasons i.e., March-September (averages of 403 mm in 2012, and 484 mm in 2013). Figure 2 shows the detailed decadal distribution of precipitations during the studied period.

The average annual direct radiation at ground level is approximately 545 kJ cm^{-2} $year^{-1}$. In Târgovişte piedmont plain, the annual variation of global solar radiation is specific to the medium latitudes with a maximum amount at noon and in the summer months (June-July) and a minimum at the extreme hours of the day and in December - the winter solstice. The continuous energetic fluxes of solar radiation at the location were determined using a PAR Quantum Sensor (range = 0-2000 µmol $m^{-2}s^{-1}$) connected to a data logger. The PAR measurements during the growth seasons are presented in Figure 3. The growth season of 2012 was characterized by a slightly higher average of daily PAR (22.4 moles m^{-2}) compared to 2013 (20.8 moles m^{-2}).

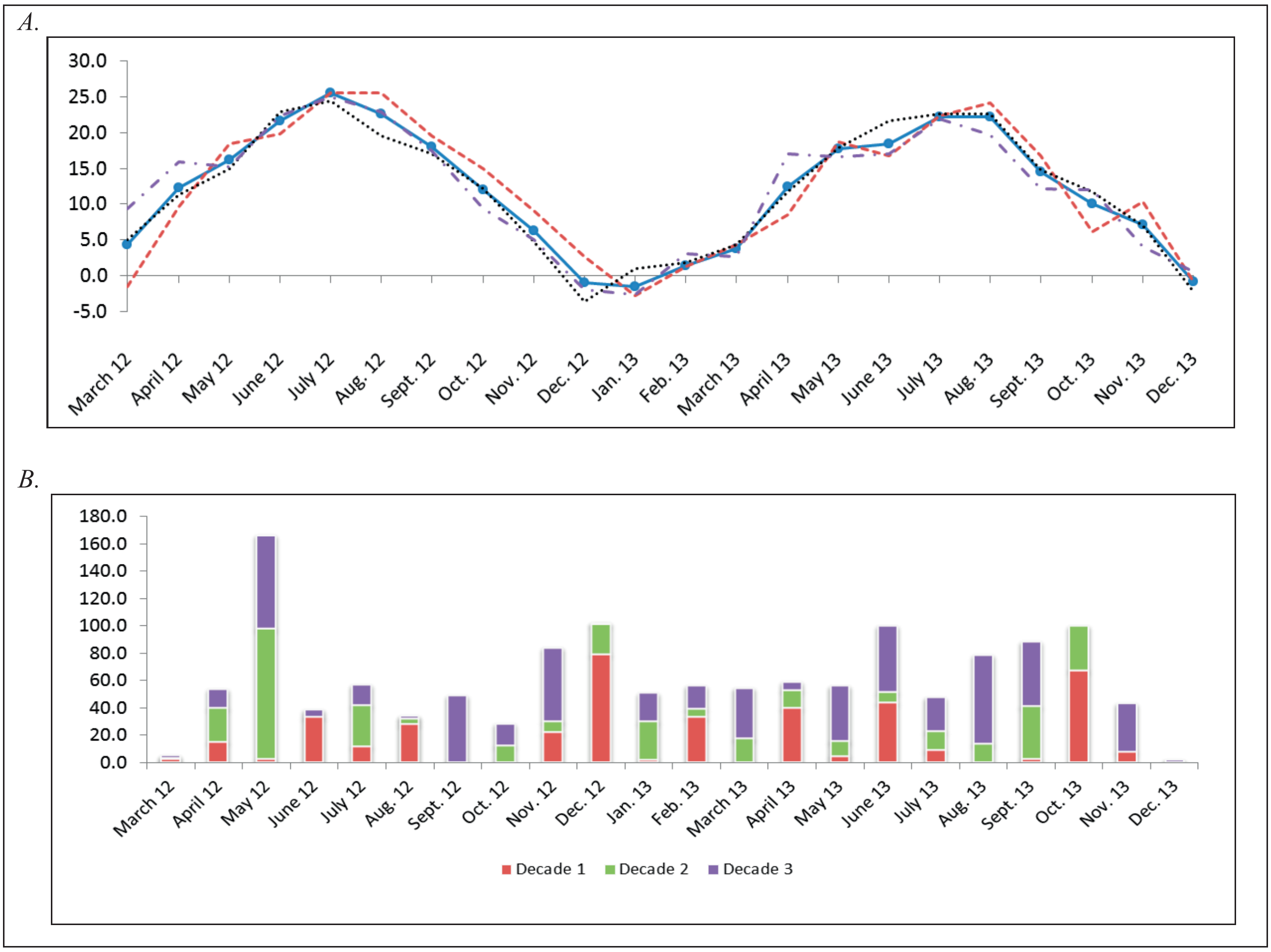

Figure 2. Meteorological data recorded during experiments (2012-2013) in Târgovişte Piedmont Plain:
A – daily average air temperature (°C); B – precipitations (mm)

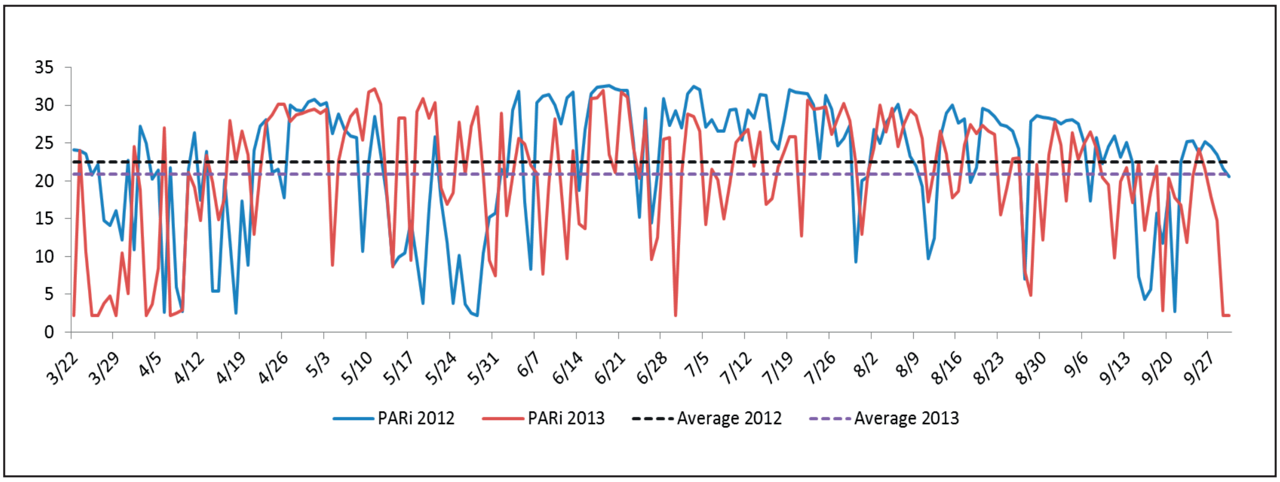

Figure 3. Photosynthetically Active Radiation intercepted by the canopy (PARi) recorded in the growth season during March-September (weekly scale) in 2012 and 2013 (moles m^{-2} day^{-1}) in Târgovişte Piedmont Plain

The quantic PAR levels in the canopy were measured using a beam fraction sensor (BF2) in conjunction with a Quantum Sensor (QS) both connected to a DL2e data logger (Delta-T Devices Ltd., Cambridge, UK) for stratified multilayer measurements. BF2 was placed outside the canopy (Figure 4), while the QS sensor was positioned at successive heights of 20 cm in the canopy from ground to top level. PAR measurements were repeated 10 times at each canopy layer to improve the accuracy of the light-extinction profile in uniform overcast conditions (UOC).

Figure 4. Beam fraction sensor (BF2) used simultaneously with a Quantum Sensor (QS) connected to a DL2e data logger (Delta-T Devices) for PAR multilayer measurements (μmol m^{-2} s^{-1}) in the canopy

The radiative balance of the alfalfa canopy in pure stand was assessed using the equations presented in Table 1.

Table 1. Main relations used to estimate the radiative balance in crop canopies (modified after Varlet-Grancher et al., 1989) - **I = EPAR or QPAR.*

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

Leaf angle distribution on the ellipsoid (ELADP) describes the tendency of leaves towards horizontal or vertical orientations.

ELADP was required to estimate the extinction coefficient (*k*) of both alfalfa varieties:

$$x = ELADP = \frac{N_h \cdot \pi}{N_v \cdot 2} \qquad (1)$$

where:

N_h – number of horizontal leaves (>45° from zenith);

N_v – number of vertical leaves (<45° from zenith).

k coefficient (Campbell, 1986) is determined as a function of *ELADP* (*x*) and the angle formed by zenith with the direct incident radiation (θ), as follows:

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

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

$$I = I_0 \exp(-k \cdot LAI) \qquad (3)$$

where:

I – the energy transmitted in crop canopy;

I_0 – incident solar radiation;

k – light extinction coefficient of PAR in the canopy;

LAI – Leaf Area Index.

The incident radiation is partially reflected with a reflectance coefficient (ρ) by the crop canopy, which is a combination of randomly distributed green leaves. ρ indicates the fraction of radiative flux which is reflected by the canopy (eq. 4 – Goudriaan, 1977).

$$I = (1 - \rho) I_0 \exp(-k \cdot LAI) \qquad (4)$$

The (*1-*ρ) fraction of the incident radiation in the visible spectrum provides the light absorption in the crop canopy. The radiative fluxes exponentially decrease inside the canopy together with the cumulated LAI from top to ground (eq. 5):

$$\rho = \left[\frac{1-\sqrt{(1-\sigma)}}{1+\sqrt{(1-\sigma)}}\right] \cdot \left[\frac{2}{1+1.6\sin\theta}\right] \quad (5)$$

where:

ρ – reflectance factor;

σ – coefficient of light diffusion for individual leaves;

θ – zenith angle of direct incident radiation.

The following elements were determined dynamically during the growth seasons as follows: *ADM* = aerial dry matter accumulated in the aboveground morphological components; *LUE* = light use efficiency, also called biological efficiency of the intercepted radiation or conversion coefficient of the quantic solar energy in yield (g ADM/moles of photons m^{-2} day^{-1}); Radiative parameters ratios (ε_i and ε_a); *k* coefficients - extinction of light in the canopy of tested cultivars; and the energy transmitted in the alfalfa canopy.

RESULTS AND DISCUSSION

Aerial dry matter accumulation

The dry matter accumulation did not show significant differences between the two tested varieties (p>0.05).

Figure 5 presents the ADM amounts recorded for each cutting in the evaluated growth seasons (2012 and 2013). Mihaela variety performed better than Roxana at the first two cuttings in each year, except the third cutting in the first year. The annual ADM production of the alfalfa varieties were 7.8 t ha^{-1} (Roxana) and 8 t ha^{-1} (Mihaela) in 2012, and 7.6 t ha^{-1} and 8.3 t ha^{-1} in 2013, respectively. Schitea (2010) reported higher yields for Romanian cultivars e.g., 14.3 t ha^{-1} in the first year, 18.2 t ha^{-1} in the second year, and 20.2 t ha^{-1} in the third year. The average of three cropping years was 17.6 t DM ha^{-1}. Such increased productions were obtained in irrigated conditions and optimal fertilization. These demonstrate the biological potential of the Romanian cultivars developed at NARDI Fundulea, as well as the importance of applying adequate cropping techniques in alfalfa.

Compared to other reported studies performed with Romanian alfalfa cultivars, our results are closer to the ones reported by Motcă (2005) that were obtained at Moara Domneasca between 2002 and 2004 in non-irrigated and non-fertilized conditions in Romanian Plain e.g., 8.4 t ha^{-1} (Roxana).

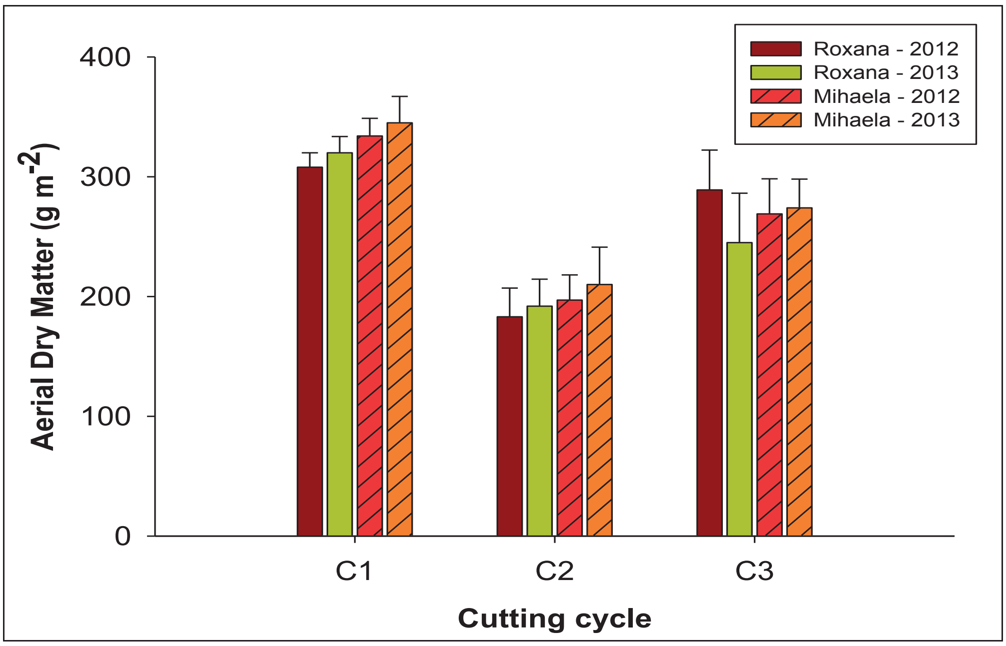

Figure 5. Aerial dry matter accumulation (g m^{-2}) of two Romanian alfalfa cultivars (Roxana and Mihaela) in the first and second year of vegetation
[Error bars show the S.E. (±) of the mean (n = 4).]

Leaf area index

Figure 6 presents the relationship between the leaf area index (LAI) and cumulated intercepted PAR of two Romanian alfalfa cultivars (Roxana and Mihaela) in the first cycle of growth. Brown et al. (2005) found that LAI of alfalfa showed a linear increase in relation to net leaf appearance (number of leaves m^{-2}). In our experiment, the LAIs of both cultivars increased with ΣPARi. The highest variations in S.E. of the mean (n = 4) was observed for an amount of 300 MJ m^{-2}, while the lowest occurred at 400 MJ m^{-2}. This stability of LAI suggests that, from that point, the plants have oriented their development towards the reproductive phenophase (Dunea, 2015). The maximum LAI at the first cutting was 5.1 for Roxana, and 5.3 for Mihaela. The results are in agreement with Schitea et al (5.3-5.6 depending on cultivar).

Other experiments established a LAI of 6 that was determined after 56 days of regrowth in late spring (bud stage) and approximately 50% of LAI was concentrated in the top canopy layer between heights of 50 and 60 cm (Woodward and Sheehy 1979). Critical LAI occurred between 30 and 40 cm at LAI of 4. The indication was that the canopy expanded leaf area in the most efficient position for a better interception of PAR (Varella, 2002; Dunea and Dinca, 2014).

Another growth mechanism of alfalfa is to maintain top leaves at intermediate to vertical angle dispersals, reducing the light saturation at the top canopy layers and allowing radiation to reach deep foliage layers (Varella, 2002).

Warren Wilson (1965) observed that the mean foliage angle dispersal of alfalfa was approximately 50° and varied little with depth in canopy. These angles have a direct influence on ELADP and light extinction coefficients. Similar leaf area characteristics of alfalfa plants were observed in our experiment.

The measurements performed in the field provided the ELADP based on eq. 1, ranging between 1.47 and 2.36 (average of varieties 1.62).

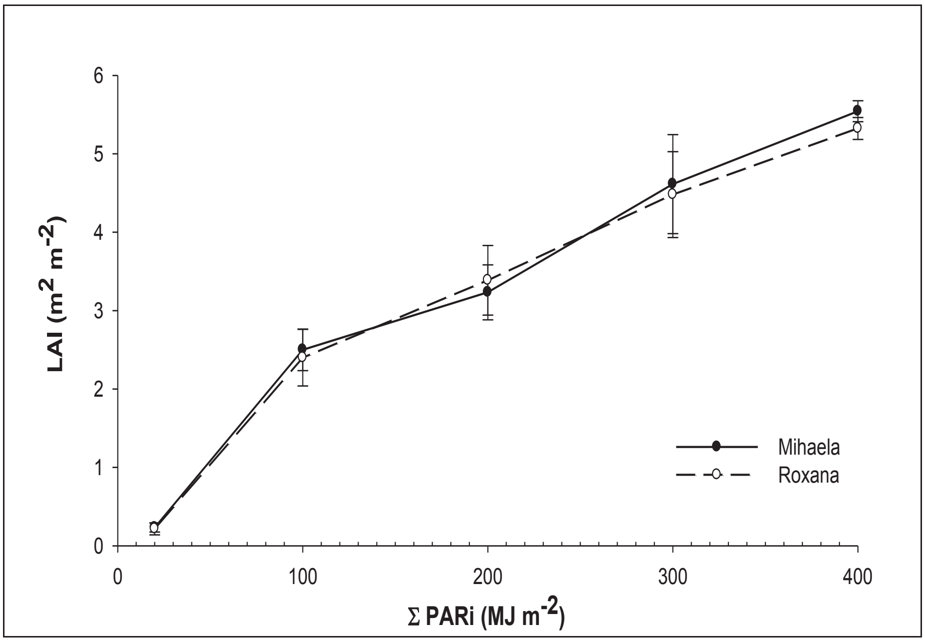

Figure 6. Relationship between the leaf area index (LAI) and cumulated intercepted PAR of two Romanian alfalfa cultivars (Roxana and Mihaela) in the first cycle of growth [Vertical bars show the S.E. (±) of the mean (n = 4).]

Campbell and van Evert (1994) reported for alfalfa an ELADP of 1.54. Coefficient *k* was estimated using eq. 2 resulting a synthetic average of 0.8 (Table 2).

A widely used value for alfalfa's *k* is 0.88 - absorbed EPAR (Gosse et al., 1986).

The energy transmitted to the canopy was computed based on eq. 3 using the measured LAI and estimated *k*.

Table 2. Extinction coefficients (*k*) calculated for alfalfa in Târgovişte Piedmont Plain for various values of leaf angle distribution on the ellipsoid (*x*) and zenith angle of direct incident radiation (θ)

Extinction coefficient (*k*)					
x \ θ	89°	85°	75°	70°	Average
1.62	0.95	0.66	0.68	0.83	0.78
2.36	0.95	0.77	0.78	0.87	0.84
1.47	0.96	0.63	0.65	0.82	0.77
Average	0.95	0.69	0.71	0.84	**0.80**

Table 3 presents the quantum of energy transmitted in the alfalfa canopy *(I)* calculated for various values of zenith angles (θ) and incident radiation (I_0 - µmol m^{-2}s^{-1}) at LAI$_{max}$ of 5. The energy transmitted to alfalfa canopy ranged between 7.4 and 22.3 µmol m^{-2}s^{-1} on average.

Table 3. Energy transmitted in the crop canopy *(I)* calculated for alfalfa in Târgovişte Piedmont Plain for various values of zenith angle of direct incident radiation (θ) and incident radiation (I_0 - µmol m^{-2}s^{-1}) at LAI$_{max}$ = 5

Energy transmitted in the alfalfa canopy (*I*)				
θ \ I_0	1500	1260	800	500
89°	8.46	7.11	4.51	2.82
85°	34.43	28.92	18.37	11.48
75°	30.91	25.96	16.48	10.30
70°	15.32	12.87	8.17	5.11
Average	22.3	18.7	11.9	7.4
St. Dev.	*12.4*	*10.4*	*6.6*	*4.1*

Figure 7 presents the light interception and absorption in alfalfa canopy (averages of both tested cultivars) in function of LAI. The resulted parameters are in agreement with the ones reported by Varlet-Grancher et al. (1989).

PAR absorption becomes relatively constant from a leaf area index of 3.3-3.5, and the reflectance diminishes with leaf area increment. In our experiment, the coefficient of absorption varied between 0.75 and 0.83 depending on variety and experimental year. Wilfong et al. (1967) reported values between 0.61 and 0.77, while Varella (2002) provided 0.82. Our results are consistent with these findings.

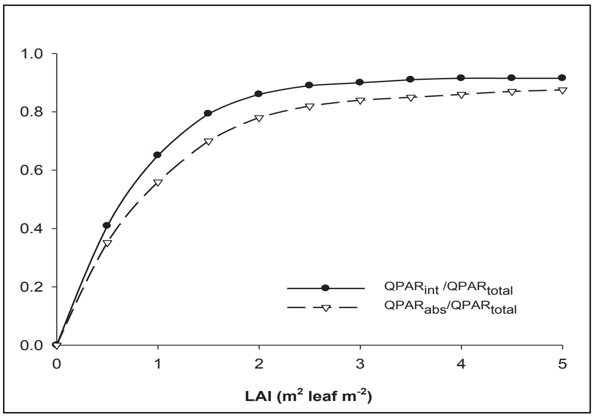

Figure 7. Radiative parameters ratios (ε_i and ε_a) depending on LAI for *Medicago sativa* L. – average of values recorded for Roxana and Mihaela varieties developed by NARDI Fundulea

Figure 8 presents the extinction of light in the canopy of two Romanian alfalfa varieties measured before the harvesting of the first cutting in Uniform Overcast Conditions and incoming radiation >1200 µmol m^{-2}s^{-1} (~ 260 J m^{-2}s^{-1}).

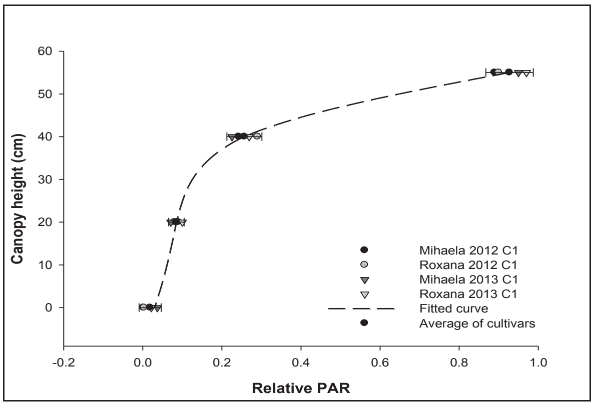

Figure 8. Extinction of light in the canopy of two Romanian alfalfa varieties measured before the harvesting of the first cutting in Uniform Overcast Conditions (UOC) and incoming radiation >1200 µmol m^{-2}s^{-1} (~ 260 J m^{-2}s^{-1})
[Horizontal bars show the S.E. (±) of the mean (*n*=4)]

The highest S.E. of mean is occurring in the top canopy layers. Both cultivars showed similar responses to light extinction in the canopy irrespective of year and genotype. At 20 cm from ground, the relative PAR in the canopy was ~0.1.

Light Use Efficiency (LUE)

Table 4 shows the LUEs of Roxana and Mihaela varieties (g moles^{-1} m^{-2} day^{-1}) cultivated in the eco-climatic conditions of Târgovişte Piedmont Plain i.e., 1st and 2nd years of cropping for each cutting cycle. Roxana showed higher values of LUE than Mihaela, with maximums in the first cycle. LUE ranged between 0.23 and 0.27 g moles^{-1} m^{-2} day^{-1} (~1.07 to 1.25 g DM MJ^{-1} with maximum in the first cycle of first year – 1.50 g DM MJ^{-1} in Roxana variety).

Table 4. Light use efficiencies (LUEs) of two Romanian alfalfa varieties (g moles^{-1} m^{-2} day^{-1}) cultivated in the eco-climatic conditions of Târgovişte Piedmont Plain (1st and 2nd years of cropping)

Alfalfa variety	Roxana		Mihaela	
Cutting /Year	2012	2013	2012	2013
First cutting (C1)	0.33	0.32	0.30	0.31
Second cutting (C2)	0.29	0.28	0.27	0.25
Third cutting (C3)	0.21	0.17	0.22	0.15
Average	**0.27**	**0.26**	**0.26**	**0.23**
Standard deviation	*0.06*	*0.08*	*0.04*	*0.08*

Brown et al. (2006) showed that estimated RUE in alfalfa had a distinct seasonal pattern, increasing from 0.80 g DM MJ^{-1} in early spring to 1.60 g DM MJ^{-1} in late summer before decreasing to 0.80 g DM MJ^{-1} in late autumn.

In dry and full sunlight conditions, Varella (2002) observed mean RUE over the experimental period of 1.06 g MJ^{-1}. Compared to other forage species, an overview of RUEs reported in literature pointed out values of 1.90 g DM MJ^{-1} m^{-2} for perennial grasses and 1.72 for legumes in pure stands (Gosse et al., 1986). White clover recorded a maximum RUE of 1.77 g DM MJ^{-1} m^{-2}, and hybrid ryegrass reached 1.8 in pure stand (Dunea et al., 2015).

Stanciu et al. (2016) found RUEs of 1.82 g DM MJ^{-1} m^{-2} for orchardgrass in mixture with alfalfa in the first cropping cycle. Mixtures of perennial grasses with alfalfa provided better interception of solar radiation during growth seasons due to the heterogeneous canopy.

CONCLUSIONS

Aerial dry matter accumulation, leaf parameters and light capture characteristics did not show significant differences between the two tested varieties ($p>0.05$) in non-irrigated conditions.

The maximum LAI at the first cutting was 5.1 for Roxana, and 5.3 for Mihaela. In alfalfa, LAI dynamics was correlated with leaf appearance, senescence rate and the size, dispersal angle and shape of individual leaves. The LAIs of both cultivars increased with the accumulation of PARi. The highest variations in S.E. of the mean was observed for an amount of 300 MJ m^{-2}, while the lowest occurred at 400 MJ m^{-2}.

The ELADP ranged between 1.47 and 2.36 (average of varieties 1.62), while k had a synthetic average of 0.8. The energy transmitted to alfalfa canopy ranged between 7.4 and 22.3 µmol m^{-2}s^{-1} on average. The coefficient of absorption varied between 0.75 and 0.83 depending on variety and experimental year.

LUE of alfalfa in Târgovişte Piedmont Plain eco-climatic conditions between 2012 and 2013 ranged between 0.23 and 0.27 g moles^{-1} m^{-2} day^{-1} (~1.07 to 1.25 g DM MJ^{-1}).

The resulted elements characterizing the light interception and absorption processes in alfalfa, which were determined dynamically in the growth seasons, are useful for the parameterisation and utilization in dedicated crop growth models.

ACKNOWLEDGEMENTS

The researches carried out for the elaboration of the present paper were financed by the Faculty of Agriculture from the University of Agronomic Sciences and Veterinary Medicine of Bucharest, Romania.

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