Net Aerial Primary Productivity Models for Alfalfa Varieties (Medicago Sativa L.) Derived from the Red Vegetation Index

This paper aimed to quantify and compare the net aerial primary productivity (NAPP) of two varieties of alfalfa (Medicago sativa L.), determine the efficient use of radiation (E) per variety, estimate the NAPP though the Red Vegetation Index and relate it to the quantified NAPP. Significant differences between the individual NAPP of each variety were not found: G969 = 1564 g ms m\(^{-2}\) and M901 = 1636 g ms m\(^{-2}\) (T = 0.92; \(p>0.05\)). The Efficient Use of Radiation (E) of the G969 was 0.56 g Mj\(^{-1}\) while that of the M901 was 0.58 g Mj\(^{-1}\). On the contrary, strong and significant direct relationships between the NAPP quantified and that calculated using the Red Vegetation Index were found. The models obtained were: NAPP\(_{G969}\) = 506.06 \(x\) – 343.25 (\(R^2 = 0.88; \ p<0.001\)) and NAPP\(_{M901}\) = 420.28 \(x\) + 37.82 (\(R^2 = 0.98; \ p<0.001\)). Though the explanatory power of these models is high, the different structural features of the alfalfas studied such as the spatial foliage distribution and the leaf inclination angle in the foliage affect its reflectance and, consequently, lower the Red Vegetation Index explanatory power.

Keywords: Reflectance, structure, lucerne, index

Introduction

Determining the net aerial primary productivity of the green vegetation in pecuary activities is fundamental to make decision at site level, particularly for assigning areas and ruling grazing pressures. However, the traditional measuring techniques, particularly the destructive ones are time demanding, increase costs and are considered as highly tedious particularly when the sampling area is increased (Sala & Austin, 2000). This is the reason why non-destructive testing techniques to determine the NAPP of pastures using sensor-derived Vegetation Indices are developed (’t Mannetje & Jones, 2000).

The close relationship existing between the NAPP and the Vegetation Indices made their use as potential productivity indicators possible (Nouvellon et al., 2000). It was done using the Monteith’s empirical model (1977) based upon the efficient use of radiation (EUR= E) which is a tool useful for quantifying the seasonal biomass production without limitations of water, temperature and fertility. According to Felsholt et al. (2003), the coefficient E is the variable showing the highest uncertainty to estimate NAPP.

Digital cameras, commercially accessible and available were effective alternatives for estimating biophysical parameters (biomass and IAF) in a non-destructive way (Przeszlowska et al., 2006). They can be considered as proxy detection sensors of high spatial and time resolution with cartesian system of capturing colors in the space, red (R), green (G) and blue (B) where the digital
numbers RGB (DN) provide a permanent and repeatable register of the plots at low cost and high accuracy (Sonnetag et al., 2011; Sakamoto et al., 2012). In accordance with Gitelson et al., (2002) the intensity of the green and red reflectance become efficient choices to those red and infrared to determine biophysical properties in agricultural crops. In this sense, either the Color or Vegetation indices synthetize the information concerning the RGB brightness obtained in using digital cameras (Sonnetag et al., 2011).

Among the early works developed out of digital cameras, it can be mentioned those by Wiegand et al. (1979) and Aase & Siddoway (1981) who found strong relationships between the IAF and the dry matter of wheat leaves using Vegetation Indices. Woebbecke et al. (1995) reached the best classification between green plants and their environment (background) using the 2G-R-B and green Vegetation Indices. In turn, Kawashima & Nakatani (1998) managed to relate the red, green and blue Vegetation Indices to the chlorophyll content of agricultural crops.

Przeszlowska et al. (2006) determined the accuracy and precision of indirect measuring methods is sites of shortgrass and compared them against the traditional cutting methods. They used images obtained by digital camera to determine areas with photosynthetically active vegetation or the Green Area Index. Ge et al. (2016) stated strong direct relationships between the 2G/(B+R) index and the estimated green area (r = 0.95), green matter (r = 0.99) and dry matter (r = 0.95) of corn (Zea mays). They concluded that the area estimated using the index and related to destructive measurements is a good estimator of green matter, dry matter and leaf area in early vegetative states (r = 0.95). Jáuregui et al. (2018), using canopy software, related light interception and the NAPP in alfalfa crops by the R/G, B/G and 2G-R-B Vegetation Index and reported the coverage percentage or foliage green area index. They obtained strong and significant direct relationships in springtime and summertime ($R^2 = 0.86; p<0.05$) and in fall and wintertime ($R^2 = 0.77; p<0.05$).

Based on the above and tending to get local information, this work aimed at: a) quantifying the net aerial primary productivity of two varieties of alfalfa (Medicago sativa L); determining the effective use of radiation per variety; c) estimating the NAPP using the Red Vegetation Index derived from the digital camera and relate it to the quantified NAPP.

### Methodology

#### Study Area

The test was carried out in the Silviculture and Forest Management Institute (Lat S 27º 52’; Long W 64º 14’), Forest Sciences Faculty, National University of Santiago del Estero, located at El Zanjón, Province of Santiago del Estero, Argentina (Figure 1). The average rainfall in the Province is of 550 mm, the annual evapotranspiration ranges between 900 and 1,100 mm with
hydrical deficit all year round. The annual average temperature is 27.7 °C (Boletta et al., 2006). The soil contains organic matter, is non-saline and slightly sodic in depth; its profile has developed onto sandy-loam fluviial sediments and shows horizons A1, AC, C1 and IIC (Angueira, 2015).

**Figure 1.** Left: Argentina in South America and the Province of Santiago del Estero in Argentina. Center: Aerial View of the City of Santiago del Estero (Red Circle) and El Zanjon (Yellow Triangle). Right: Test Location (Red Circle), the Silviculture and Forest Management Institute, FCF, UNSE (Lat S 27º 52'; Long W 64º 14’).

Source: NDVI Modis Terra Map & Google Earth.

### Quantified Net Aerial Primary Productivity

In April 15, 2018 two commercial varieties of alfalfa (*Medicago sativa L*) belonging to the group nine of dormancy G969 (www.gapp.com.ar) and to Magna 901 (www.forratec.com.ar) in an average density effective and homogeneous of 350 individuals per square meter following a totally randomized design in 1.5 m² plots with eight repetitions per variety. To minimize the factors affecting pasture biomass productivity and, consequently, the UER (Monteith, 1977) they were irrigated and fertilized while sowing with 100 kg ha⁻¹ of NPK (16.7.15). Monthly post-harvest irrigations of aprox. ~50 mm irrigation⁻¹ were carried out. The green biomass, or the net aerial primary productivity of each variety was cut and weighed at the preflowering stage and dried afterwards (‘t Mannetje & Jones, 2000). Annual Net Primary Aerial Productivity of each variety, were temporarily integrated and expressed in grams of dry matter per square meter (g dm m⁻²). The means of the NAPP (hopes) between varieties (distributions) were evaluated using the T-test for independent samples (Di Rienzo et al., 2011).

### Camera Technical Programming and Photography

The images were got using a D7100 Nikon Digital Reflex Camera (Nikon Corporation, Tokyo, Japan) with a built-in CMOS image sensor of 23.5 x 15.6 mm, 24.1 real megapixels, an AF-S NIKKOR lens of 18-300 mm f/3.5-5.6G EDVR. The size of the selected photogram wasd of 2.304x1,536 pixels in
RAW format (Nikon Electronic Format), 14 bit depth, 24 bit RGB resolution (Ahrends et al., 2009). The camera was set up in automatic mode and an ISO 200 sensibility (Sakamoto et al., 2012).

The camera was geometrically setup onto a vertical tripod using bubble levels and angle graduation at 1m above the foliage top; the sensor was oriented to each plot center with a 0° inclination angle (Rasmussen et al., 2007) (Figure 2). The images were shot previous to the cut in cloud-free days at the solar noon from 10.00 AM to 2.00 PM (Inoue et al., 2015). The white balance of the images was adjusted using the 18% Gray Balance reflectance card (X-Rite corporation) placed at the central area of every plot (Inoue et al., 2015) (Figure 2).

Image Processing and Digitization

The camera sensor calibrating profile was generated out of a standard Color Checker Passport (X-Rite, Incorporated) color reference image. All the images were linearly adjusted in spectral terms using the sensor calibrating profile (DGN) using the Adobe Camera Raw software and saved as a TIFF (Tagged Image File Format) document standardized at 8 bit (Min 0; Max 255) and then classified using the ImageJ software (Ferreira & Rasband, 2016). The value obtained for the green aerial forage biomass, i.e. the photosynthetically active vegetation (Baret et al., 2010), was one (1) while zero (0) for the remainder background. From the resulting binary image, digital numbers (DN) were extracted using the digital sampling polygon (Sonnetag et al., 2011) (Figure 2).

Figure 2. Top A) RGB Image at 0° and 18% Gray Balance Reflectance Card; B) Binary Image of A. Bottom: Red, Green and Blue Bands with Sampling Vectors (Red)
The Vegetation Index Red

The DN of the RGB images were strongly influenced by the scene lighting; to suppress such an effect, a non-linear transformation of RGB to the r, g and b color coordinates (Gillespie et al., 1986; Woebbecke et al., 1995) was made. The chromatic coordinates r, g and b were obtained from Equation 1:

\[ R^* = R/R_m; \quad G^* = G/G_m; \quad B^* = B/B_m, \]

where \( R^*, G^* \) and \( B^* \) stand for the normalized RGB values (0-1) defined as \( R^* \) = \( R/R_m \); \( G^* \) = \( G/G_m \); \( B^* \) = \( B/B_m \), being \( R, G \) and \( B \) the digital levels of the photosynthetically active vegetation of the study area, respectively whereas \( R_m = G_m = B_m = 255 \) the tonal maximum value of the (8 bit) primary colors (Gillespie et al., 1986; Woebbecke et al., 1995). In this work, the red color coordinate was used as the Red Vegetation Index (Tucker, 1979).

The Predicted Net Aerial Primary Productivity

Many studies analyzed the direct relationship existing between the Vegetation Indices and the NAPP (Tucker, 1979) expressed by equation 2 as:

\[ \text{PPNAPredicted (g dm}^{-2}\text{)} = \varepsilon^* \sum \text{NDVI}_{ij} \quad (2) \]

By replacing the Normalized Green Index in Equation 2 by the Red Vegetation Index, Equation 3 results as:

\[ \text{PPNAPredicted (g dm}^{-2}\text{)} = \varepsilon^* \sum \text{VI red}_{ij} \quad (3) \]

where \( i \) stands for the integrated Red Vegetation Index of each cutting and variety of the decrease stage \( j \) (i.e. from April 2018 to February 2019).

The values for the Efficient Use of Radiation (\( \varepsilon \) (g Mj\(^{-1}\))) in the study area are limited because they were derived for each variety using the Monteith’s Model (1997) of Equation 4:

\[ \varepsilon (\text{g Mj}^{-1}) = \frac{\text{PPNAQuantified (g m}^{-2}\text{)}}{\text{PAR (Mj m}^{-2}\text{)}} \quad (4) \]

where NAPP stands for the quantified aerial biomass productivity, annually integrated for each repetition and variety. The annual average incident solar radiation over the study area is of 5832 Mj m\(^{-2}\) (Righini y Grossi Gallegos, 2011). The annual average photosynthetically active incident radiation over the foliage is of 2799.36 Mj m\(^{-2}\) (PAR) which is a constant fraction of 48\% of the global incident radiation on the border of the atmosphere (Fensholt et al., 2003).

The Quantified vs the Predicted NAPP Relationship

The quantified NAPP (dependent variable \( y \)) and that predicted (independent variable \( x \)) were related by means of the simple linear regression
method (α 0.05). The lineal models were tested based on the best adjustment of the coefficient of determination and by observing the scatter plots (residuals vs. predicted) (Di Rienzo et al., 2011).

**Results**

*Net Aerial Primary Productivity of the Varieties*

Seven cuts per variety of alfalfa were analyzed between September 15, 2018 to February 4, 2019. In April 2019 both pastures were totally lost for excessive rainfall. Significant differences were not found in the NAPP between varieties (T = 0.92; p>0.05). The average NAPP of the variety G969 was of 1564 g dm m\(^{-2}\) while the variety M901 yielded 1636 g dm m\(^{-2}\).

**Efficient Use of Energy (\(\varepsilon\))**

The Efficient Use of Energy of the variety G969 was \(\varepsilon = 0.56\) g Mj\(^{-1}\) while the minimum and maximum values were 0.43 g Mj\(^{-1}\) y 0.64 g Mj\(^{-1}\), respectively. That of the variety M901 was \(\varepsilon = 0.58\) g Mj\(^{-1}\) and the minimum and maximum values were 0.51 g Mj\(^{-1}\) y 0.66 g Mj\(^{-1}\), respectively. It should be highlighted that, in this work, fall productivity was not quantified due to excessive rainfall.

*The Quantified-Predicted NAPP Relationship (Ratio)*

Strong and significant direct relationships between the quantified NAPP of both varieties and that estimated using the empirical model (Figures 2-3). The graphs of dispersion below showed random patterns of distribution.

The resulting models are introduced by Equations 5 and 6 below:

\[
\text{NAPP}_{G969} = 506.06 \times - 343.25 \quad (R^2 = 0.88; p<0.001) \quad (5) \quad (\text{Fig. 3}),
\]

\[
\text{NAPP}_{M901} = 420.28 \times + 37.82 \quad (R^2 = 0.98; p<0.001) \quad (6) \quad (\text{Fig. 4}).
\]

**Figure 3. The G969 Variety Linear Regression Model between the Estimated and the Predicted NAPPs**
Figure 4. The M901 Variety Linear Regression Model between the Estimated and the Predicted (Ɛ* IV Red) NAPPS

Discussion

The average yields obtained range about those average values for alfalfa determined by the National Institute of Agricultural Technology in the study area. The average NAPP values estimated by the Alfalfa Crop Net Group 9 in the periods indicated were as follows: 2014/2015 = 2222 g dm m^2 (Cornachione, 2015); 2015/2016 = 1884 g ms m^2 (Cornachione, 2016); 2016/2017 = 1980 g dm m^2 (Cornachione, 2017) and 2017/2018 = 980 g dm m^2 (Cornachione, 2018).

Since the Ɛ values for the study area are scarce, the results obtained here become relevant and, according to Nouvellon et al. (2000) allow to lower uncertainty in the generation of predictive models. The EUR for temperate pastures (Ɛ = 0.63 g Mj^-1) determined by Ruimy et al. (1994) outstands; it ranges within the maximum and minimum Ɛ values obtained for each variety in this work.

According to Collino et al. (2007), the variations of the Ɛ can be endorsed to such factors as variety, radiation and temperature regimes, direct-diffuse radiation rate and differences in the partition between foliage and storing organs (crown and roots). In turn, Druille et al. (2019) inform that the Ɛ values mostly respond to the genotype and directly or indirectly to resource management and availability. Brown et al. (2006), in quantifying the influence of the seasonal variation on the solar radiation, temperature and the biomass partition of the alfalfa irrigated, found a strong direct lineal relationship between the NAPP of the alfalfa (R^2 = 0.93) and the total intercepted radiation, the Ɛ ranged from 0.29 g Mj^-1 to 1.09 g Mj^-1.

The authors concluded that the NAPP is highly affected by the variation of the incident solar radiation (seasonality) and by the air temperature in temperate environments. In this sense, Bat-Oyun et al. (2012) determined for natural pastures in semiarid settings a wide range of Ɛ (0.23 g Mj^-1 – 1.06 g Mj^-1) that was affected by water and thermal stress, together with a maximum Ɛ value of 2.34 g Mj^-1 without thermal and water stress. The seasonal effect was
evaluated by Khaiti & Lemaire (1992) who determined that the $\varepsilon$ varies from
0.79 g Mj$^{-1}$ in the post planting stage, to 1.8 g Mj$^{-1}$ for the summer regrowth, to
an intermediate value of 1.13 g Mj$^{-1}$ for the fall regrowth and to a constant
value of 2.4 g Mj$^{-1}$ for the total NAPP in alfalfa.

At regional level, Collino et al. (2005) determined in Cordoba, Argentina,
that the $\varepsilon$ for the Monarca SP INTA crop (group 8 of dormancy) was of 0.81 g
Mj$^{-1}$ in fall, 0.62 g Mj$^{-1}$ in winter, 1.28 g Mj$^{-1}$ in spring and 1 g Mj$^{-1}$ in summer.
The $\varepsilon$ of the Victoria SP INTA crop (group 6 of dormancy) fluctuated between
0.6 g Mj$^{-1}$ and 1.3 g Mj$^{-1}$, decreased linearly below 21.3°C and stabilized in 1.3
within an average range of optimal temperatures of 21.3 °C and 26.5 °C. The
authors conclude that such a wide range of EUR occurred because of the high
variation in the annual temperatures and the distribution of photo-assimilates.
Pece & Cangiano (2002), on their part and using the same crop found the same
trend in SE Buenos Aires, Argentina, though with values of EUR oscillating
between 1.1 g Mj$^{-1}$ and 1.97 g Mj$^{-1}$.

Because of the arid conditions of the study area, and of the NW Argentina
in general, the edaphic water availability appears as the limiting factor; without
such a limiting factor, all the varieties of alfalfas respond with a high EUR in
both fall and summer. However, in accordance with Collino et al. (2007), the $\varepsilon$
is affected by low temperatures and photo-assimilates mobility in fall and
winter.

The explanatory force ($R^2$) of both models is high (Equations 5 and 6);
however, the model of the variety M901 is much higher. What is this difference
owed to since both varieties were treated under similar environmental
conditions (irrigation, fertilization, seasonality, sanity and management). At the
time the photogram was shot, the solar lightening geometry was considered,
and the sensor calibrated (Jackson et al., 1983). Therefore, such a difference
would be related to structural variations of the varieties such as foliage
geometry and leaves distribution affecting both its reflectance and consequently
the Vegetation Index (Bannari et al., 1995).

In this sense and according to their respective seedbeds, the variety M901
has a semi-upright aspect while the G969 an upright one since both varieties
arrange differently in space. The semi-upright M901 variety shows a green leaf
area larger than that of the upright variety when the photogram is taken at a 0°
angle. In this sense, Inostroza et al. (2018) found strong and significant inverse
relationships with the Lab-b ($r = 0.56$, p<0.001), HUE ($r = 0.58$, p<0.001),
Luv-v ($r = 0.55$, p<0.001) and green area ($r = 0.36$, p<0.01) indices when
evaluating the phenotypical relationship between the Vegetation indices
derived from the RGB digital camera and the NAPP of sixty-three populations
of alfalfa. The authors concluded preliminary that the digital camera derived
RGB Vegetation Indices are phenotypically associated to the NAPP. However,
it should be noted that Stevens et al. (2007) do not recommend utilizing indices
derived from the conversion to other values of color in the space as HSB (hue,
saturation and brightness) because of their high inaccuracy.
In preliminary studies by Tiedemann (2018), strong and significant inverse relationships ($r = -0.92; p<0.01$) between the integrated NAPP of the G969 alfalfa and the RGB Vegetation Indices (i.e. Red, REI, T and SUM) were found. The resulting linear models showed high explanatory force ($R^2 Aj = 0.81; p<0.01$). Additionally, Tiedemann (2018a) ($Triticum aestivum L$) found strong and significant direct relationships ($p<0.01$) between the NAPP of the Serpiente variety of wheat and the Total and red indices; the $R^2$ varied between 0.92 and 0.96. Following the same work line, Tiedemann (2019) detected strong and significant ($p<0.01$) direct relationships between the Red, REI, T and SUM Vegetation Indices taken at $0^\circ$ and $45^\circ$ and the NAPP of the Mercurio wheat crop. The resulting linear models at a $0^\circ$ angle showed an $R^2$ that ranged from 0.75 to 0.67, while at $45^\circ$, the $R^2$ varied between 0.67 and 0.70.

**Conclusions**

The values for the $\varepsilon$ of the alfalfa varieties under study, determined at local level, gain relevance due to the absence of locally estimated values. These reduce uncertainty when predictive models of productivity are generated.

The linear models obtained allow to quantify the NAPP of alfalfa varieties on field and non-destructively.

The various structural features of the alfalfa varieties studied such as their spatial distribution of leaves and their leaf inclination angle in the foliage affect their reflectance and, consequently, the Red Vegetation Index and its explanatory force.

**References**


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https://doi.org/10.2134/agronj1979.00021962007100020027x