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A chromaticity-based technique for estimation of above-ground plant biomass

Tomasel, F.G.[1,3*]; Paruelo, J.M.[2,3]; Abras, G. [4]; Ballarín, V.[4] & Moler, E.[4]

[1]*Departamento de Física, Facultad de Ingeniería, Universidad Nacional de Mar del Plata, Juan B. Justo 4302, 7600 Mar del Plata, Argentina;* [2]*IFEVA and Cátedra de Ecología, Facultad de Agronomía, Universidad de Buenos Aires, Av. San Martín 4453, 1417 Buenos Aires, Argentina;* [3]*Research Scientist of the Consejo Nacional de Investigaciones Científicas y Técnicas (CONICET);* [4]*Departamento de Ingeniería Electrónica, Facultad de Ingeniería, Universidad Nacional de Mar del Plata, Juan B. Justo 4302, 7600 Mar del Plata, Argentina;*
[*]*Corresponding author; Fax +542234810046; E-mail tomasel@ieee.org*

Abstract. This paper presents a new and simple technique to derive quantitative estimates of green or dry biomass using colour information from digital pictures. This pixel-counting technique is based on the association of particular plant material with a representative region on a two-dimensional colour space, and applies to cases of non-overlapping canopies. The efficacy of the method is demonstrated using sets of samples obtained from both field and laboratory studies. It is shown that application of the proposed approach results in a highly linear relationship between pixel count and foliar area for both green and non-green material [$r = 0.99$ ($p < 0.001$)]. Analysis of images from a short-grass steppe shows a high correlation between pixel count and measured values of green biomass [$r = 0.95$ ($p < 0.001$)]. The method outlined here allows for a substantial improvement in the speed of sample evaluation to estimate biomass both in the field and in the laboratory. It also provides a non-destructive alternative to monitor plant cover and biomass in open canopies.

Keywords: Colour classification; Non-destructive method; Primary production estimation.

Abbreviations: CIE = Commission Internationale de l'Eclairage; NDVI = Normalized Difference Vegetation Index; RGB = Red-green-blue.

Introduction

Green and dry biomass are two basic attributes that can be used to characterize a plant canopy in ecological, agronomic or applied studies. Green biomass provides information on many key structural and functional aspects of the systems such as the amount of light intercepted or the availability of forage. Repeated measurements of green and dry biomass are the basis of estimates of net primary production (Sims et al. 1978; Sala et al. 1981; Sala et al. 2000; Lauenroth et al. 1986). Field measurements of these attributes are tedious and time consuming, and much effort has been devoted to the development of double sampling techniques to estimate biomass (Ahmed et al. 1983; Catchpole & Wheeler 1992; Murphy et al. 1995). This approach involves the development of a regression equation between biomass and an easily measured variable. The variables that are commonly used include ground cover, sward height, total blade length per tiller and point contacts (Pasto et al. 1957; 't Mannetje 1976; Williamson et al. 1987). Remote sensing techniques based on hand-held radiometers and the use of spectral indices, such as the Normalized Difference Vegetation Index (NDVI), provide an alternative to obtain green biomass estimates in a much easier way than clipping (Tucker 1977; Asrar et al. 1984, 1985). NDVI provides an estimate of the fraction of the photosynthetically active radiation intercepted by green tissues (Sellers et al. 1992). Given the same amount of green biomass, dry biomass would show a reduced NDVI that reflects changes in biophysical rates, such as primary production. However, the specific relationship between NDVI and the light intercepted by the canopy reduces the suitability of this index to estimate green biomass or leaf area, and the nature of the index precludes its use as an estimator of dry biomass.

Paruelo et al. (2000) presented a non-destructive, photographic method to estimate green biomass in grasslands. The method allows for a dramatic increase in the number of samples per operator compared to the clipping method, the traditional way to get biomass estimates. The method is based on a relationship between green pixel count in a digital image and green biomass. In this approach, devised exclusively for the classification of green material, green pixels are defined as those whose red *(R)*, green *(G)*, and blue *(B)* values satisfy the inequalities $G > R$ and $G > B$.

This paper presents a simple alternative to derive quantitative estimates of green and/or dry biomass from digital pictures. This chromaticity-based technique allows for an easy classification of pixels regardless of their colour. Although it includes the Paruelo et al. (2000) method as a particular case of colour classification, its direct application is still limited to sparse, flat vegetation where cover correlates with biomass. However, it is shown that introducing a harvesting and photographing methodology for closed canopies can circumvent this limitation. The application of colour analysis described herein results in better and faster estimates of green biomass and makes possible the quantification of biomass of non-green material.

Material and Methods

The technique

Estimation of the biomass was based on colour information coded in the digitized images of the vegetation. Colour information is usually specified by the coefficients of a linear combination of three basic or primary colours. This representation is found in most applications of digital image processing (Jähne 1996). In the case of self-luminous displays such as monitors, colours are generated by addition of red, green and blue primaries corresponding to the phosphor compounds used in the cathode ray tubes. This colour coding system is usually called RGB.

Alternatively, a colour can be specified by its luminance component *Y*, related to the brightness, and two additional components *X* and *Z*. The Commission Internationale de l'Eclairage (CIE) defined a system based on this approach in 1931, and it has been a standard for colorimetry since then. Although any colour can be described by its *XYZ* components, it is sometimes convenient to analyse 'pure' colours, in the absence of brightness. The operation of normalizing the colours by the intensity reduces the 3-D colour space to a 2-D colour plane, called the chromaticity diagram:

$$x = \frac{X}{X+Y+Z}, \quad y = \frac{Y}{X+Y+Z}, \quad z = \frac{Z}{X+Y+Z}, \quad (1)$$

where $x + y + z = 1$ (Fig. 1). All the visible colours fall in a wing-shaped region in the *x*, *y* space. The curved boundary is formed by all the visible monochromatic colours, while the straight edge consists of the non-spectral purples. White is at the centre. In this diagram, purity of a given colour is proportional to its distance from the white point; in such a way that spectral colours have purity one, while white has purity zero. All the colours in this diagram are at unit intensity, hence there are no intensity-related colours such as brown.

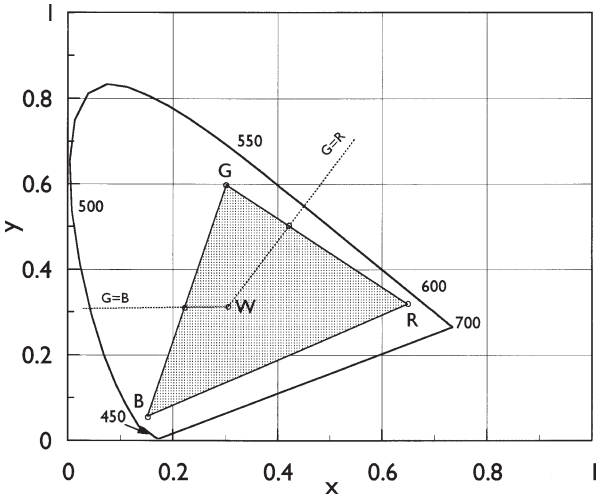

Fig. 1. Schematic version of the CIE chromaticity diagram showing the wavelengths corresponding to some of the pure colours of the visible spectrum. Letters R, G, and B indicate the loci of the colour TV primaries. The colours that can be obtained from these *R, G* and *B* primaries lie in the shaded region. The top portion of this triangular region, bounded by the $G = R$ and $G = B$ lines, represents the classification criterion $G > R$, $G > B$ used by Paruelo et al. (2000) in the identification of green pixels. Wavelengths are in nanometers.

The points indicated as R, G, and B in Fig. 1 denote the position of the primary colours used by most contemporary colour computer monitors. As it was mentioned before, in self-luminous displays colours are obtained by linear combination of these three primaries. It is important to note that in general, when the coefficients of such a linear combination are restricted to positive values, some colours cannot be represented as a combination of visible primary colours. Therefore, a monitor will not accurately reproduce all the visible colours. The colours that can be obtained from a particular set of RGB primaries will be determined completely by the colour of the primaries themselves, and will be restricted to a triangular region inside the chromaticity diagram (see Fig. 1).

Although in the RGB representation all colours present in a given image lie in a 'colour cube', identification and grouping of a given set of colours found in the image may not be evident in this representation. Besides, in many cases the information of intensity or brightness is not relevant to the analysis. In the case presented herein, identification and classification were performed by restricting the colour analysis to the chromaticity diagram. The original RGB space was mapped into the 2-D chromaticity diagram using a linear transformation based on international agreements on primaries for high definition television, which are representative of

Table 1. Standard values for the primaries and white point of the RGB system (Anon. 1990).

	R	*G*	*B*	*White*
X	0.640	0.300	0.150	0.3127
Y	0.330	0.600	0.060	0.3290
Z	0.030	0.100	0.790	0.3582

contemporary computer monitors (see Table 1).

The first step in the identification of a particular type of plant material was to find its representative colour wedge on the chromaticity diagram. This calibration procedure was performed on one picture, and it was carried out once for every type of plant material to be identified. After calibration, all the remaining pictures were analysed. Pixels whose colour fell into the calibrated colour region were identified as positive and counted. All the calculations were performed by simple routines written in MATLAB™.

The data

The technique was evaluated using two sets of data. First, the data used by Paruelo et al. (2000) in the quantification of green biomass was re-analysed. Then, a second set of images that included both green and dry biomass was generated and analysed to evaluate the capability of the technique to estimate non-green biomass.

The data set from Paruelo et al. (2000) was generated to address the problem of field measurement in cases of canopies with a low coverage. In these cases of sparse, flat vegetation where cover correlates with biomass, a correct identification of the pixels corresponding to the leaves is expected to result in a highly linear relationship between pixel count and biomass. The data were collected in the Central Plains Experimental Range in northcentral Colorado, USA (40º 49' N, 104º 46' W). Mean annual precipitation is 321 mm (SD = 98 mm). Average annual temperature is 8.6 °C (SD = 0.6 °C). The vegetation is typical of the northern portion of the short-grass steppe. The dominant species is the perennial bunchgrass *Bouteloua gracilis*. Important associated species include *Buchloë dactyloides*, *Opuntia polyacantha*, *Sphaeralcea coccinea* and *Carex eleocharis*. Photographs were taken for two dates during the growing season: June 10 and June 26, 1996. Circular plots 0.56 m in diameter were photographed using a 35-mm reflex camera (PENTAX PZ10) with a 28-70 mm zoom lens. The camera was mounted on a tripod and positioned facing down 1.4 m above the ground, forming an angle lower than 10 degrees from the vertical. Colour slide film was used for the pictures (Kodachrome 200 ASA). Pictures were taken between 11:00 AM and 3:00 PM on clear days. The slides were digitized and converted to colour bitmap files (BMP), at a resolution such that each individual pixel corresponded to a ground area of ca. 0.25 mm^2. Above-ground biomass was harvested from each plot after the picture was taken. Plants were clipped at soil level and green biomass was sorted into the following groups: grasses, forbs, lichens and cacti. After sorting, material was oven-dried at 50 °C and weighted.

Estimation of biomass for closed, overlapping canopies cannot be performed by direct application of our pixel-counting approach, since in these cases vegetation cover remains invariant while biomass may increase with vegetation height. This limitation can be overcome if the canopy is harvested and the photographic technique is applied to the clipped vegetation: instead of sorting out green, dry and dead material in the laboratory, the cut material can simply be spread on a contrasting background and photographed. Biomass can then be estimated directly from the picture, speeding up the often tedious process of separation of the cut vegetation for drying and weighting. To show the applicability of the technique to these cases, a set of 10 samples with different green-to-dry biomass ratios were prepared using green and senescent material from a *Bromus unioloides* sward. The material was mixed and spread on a paper sheet of a distinctive colour, and then photographed using a digital camera (SONY Mavica MVC FD7).

Results and Discussion

Fig. 2 shows, in a qualitative fashion, the recognition ability of the algorithm in a typical picture of the short-grass steppe. Although the full capabilities of the technique cannot be appreciated from gray-scale pictures, it can be seen that the algorithm is suitable for classification problems such as the one presented here.

The effectiveness of the technique for the classification of green biomass was quantitatively analysed by comparing the results from the pixel count with the dry weight of green grass biomass collected from the sampled sites. For this purpose, a representative picture was used to adjust the size of the colour wedge so that the particular range of green colours shown by the grasses was included (Fig. 3). The highly linear behaviour of the relationship between these two quantities is evidenced by its correlation coefficient of 0.95 ($p < 0.001$). A linear regression analysis of the predicted vs. observed biomass values resulted in a slope of 0.91 and an intercept of 1.6 g, while the standard deviation of the fractional residuals was 0.22. The fitted line did not differ significantly from the 1:1 line ($p < 0.01$).

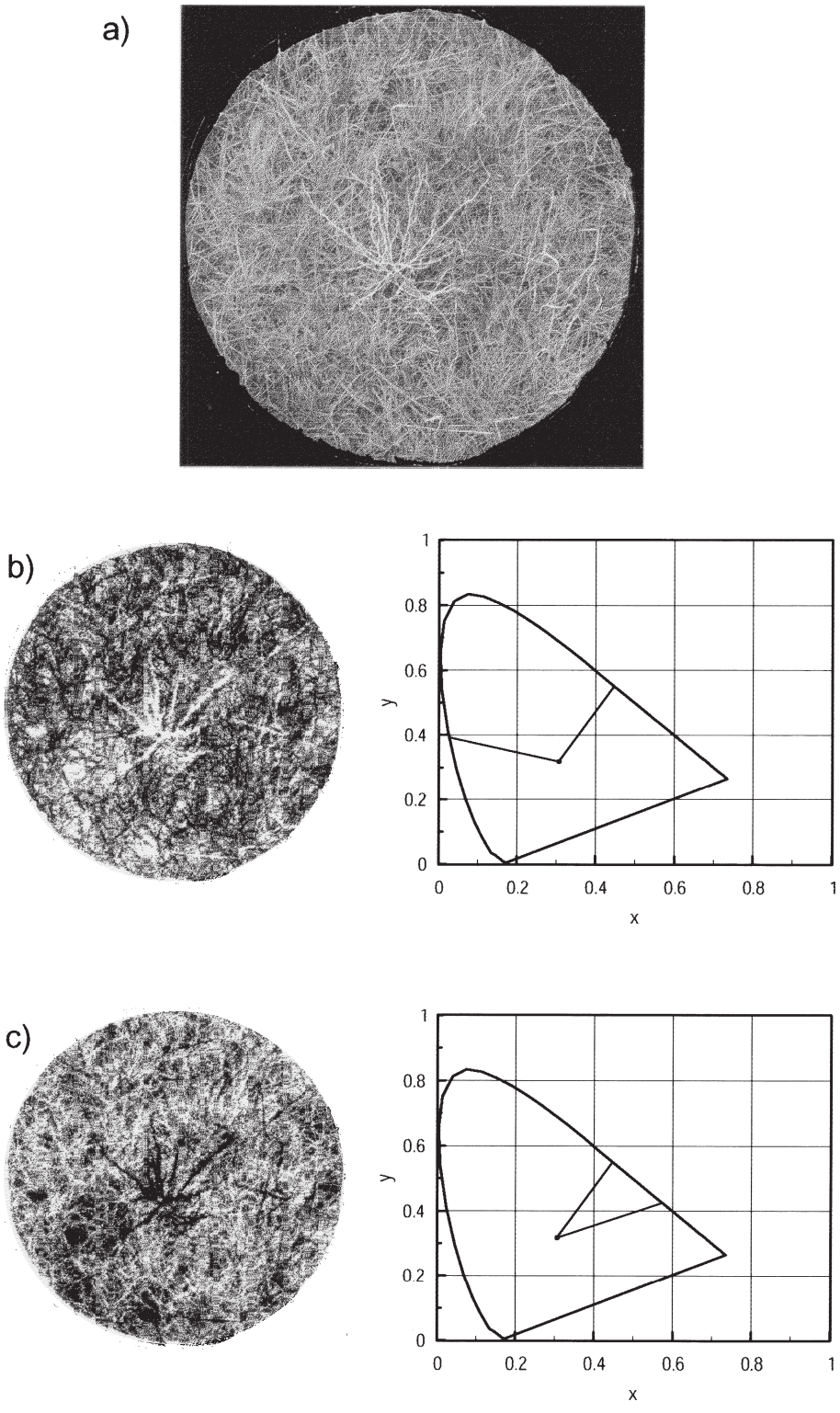

Fig. 2. Illustration of the classification abilities of the algorithm in a typical picture of the shortgrass steppe. **a.** Gray-scale version of the original colour picture. **b.** Transformed image where green pixels were identified as those whose colours belonged to the wedge indicated. These pixels were coloured in black, while the colour of the remaining pixels was set to white. **c.** Identification of dead material from the same picture. The pixels whose colour fell into the wedge indicated on the right side of the figure were identified as positive and marked in black, and everything else was set to white.

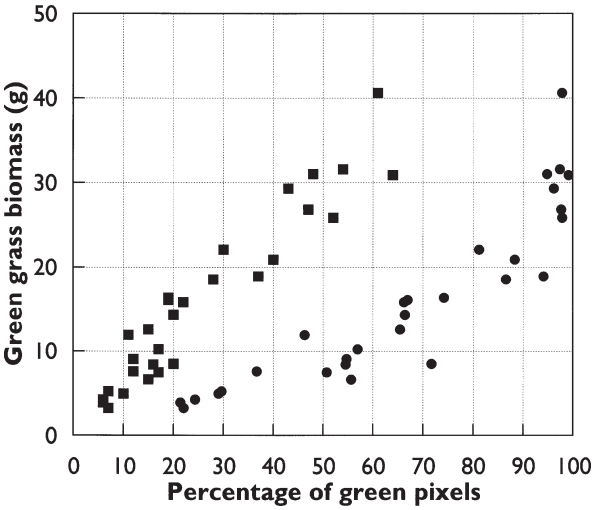

Fig. 3. Percentage of pixels classified as green versus measured values of green grass biomass. The squares represent the result of the technique described herein, while the circles indicate the results obtained using the estimation method described in Paruelo et al. (2000).

Fig. 3 also shows the results of estimating the green biomass by using the technique recently proposed by Paruelo et al. (2000). The comparison shows that, even when the latter technique is relatively easier to implement, it results in a non-linear relationship that leads to an early saturation. Saturation is due to a slight overestimation of the number of pixels associated with the particular range of green colours exhibited by the grasses. This overestimation arises from the fact that in the $G > R$, $G > B$ technique the colour wedge used for pixel classification is fixed, and it does not depend on the particular colour content of the vegetation present in the picture. The region satisfying these conditions is shown in Fig. 1. Comparing this region with the one used to analyse Fig. 2b, it can be noticed that the $G > R$, $G > B$ criterion counts as positive pixels with a higher content of blue, which lie outside the optimum classification region. In contrast, the technique described herein allows for a more precise definition of the colour region of interest, and results in a linear relationship for the full range of coverage explored. For higher degrees of coverage, saturation is expected to occur at some point due to the increasingly overlapping structure of the canopy.

To evaluate the potential of the proposed technique in the quantification of green and non-green biomass, a set of 10 images containing green and dry material was analysed. Using one of the pictures from this data set generated in the laboratory, two colour wedges representative of the green and dry material were selected, and then used to classify the remaining samples. The results are shown in Fig. 4 where, for the sake of clarity, data from five representative samples are shown. As in the case of the field data, the classification results in a highly linear relationship between the number of positive pixels counted and the foliar area measured directly on the samples [$r = 0.99$, ($p < 0.001$)]. A least squares fit to the predicted vs. observed data resulted in slopes of 1.0 and 0.96 and intercepts of 1.2 and 11.6 cm^2 for dry and green material, respectively. The standard deviation of the fractional residuals was close to 4% in both cases. As in the case of the field data, the fitted line was not significantly different from the 1:1 line ($p < 0.01$).

In summary, these results indicate that chromaticity-based pixel counting techniques can be effectively used as reliable estimators of plant biomass in field situations where there is no significant overlapping in the canopy structure. Pixel-counting techniques are a variation of the point-quadrat method (Greig-Smith 1983). With this method, biomass is calculated from the ratio between the number of hits on green tissue and the total number of observations. In the technique presented herein, counting the number of green pixels dramatically increases the total number of observations. The area sampled in this study included more than 70 000 green pixels.

As with the point-quadrat method, counting green pixels on a picture is a non-destructive method, which makes it especially suitable for long-term studies of plant cover or biomass. The combination of digital colour cameras, notebook computers and estimation methods based on colour analysis has the potential for increasing the efficacy of field studies of patch dynam-

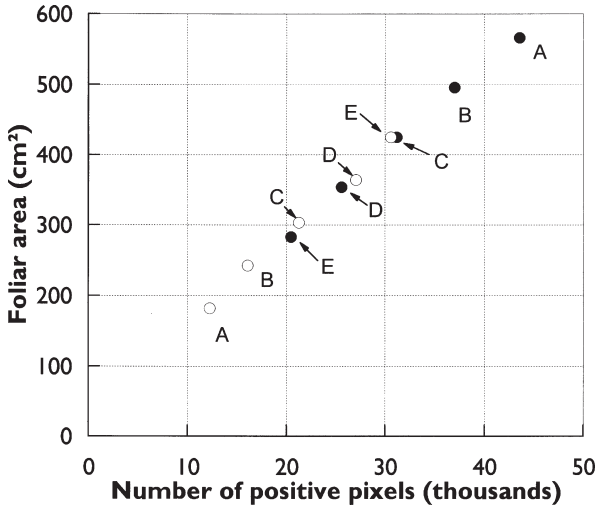

Fig. 4. Number of pixels classified as dry (solid markers) and green (open markers) tissue versus measured values of foliar area for each biomass category. Green and dry data from the same sample are labeled with the same capital letter. The measured green-to-dry foliar area ratios in these samples are as follows: A = 0.32, B = 0.49, C = 0.70, D = 1.03, and E = 1.50.

ics in arid and semi-arid systems. The short-grass steppe presents a canopy structure near ideal for this type of analysis. However, as the overlapping of leaves increases, there will be a point where the relationship between the number of green pixels and the estimated value for the biomass will saturate. Additional variables such as canopy height or the use of oblique views of the canopy may help in the quantification of biomass using pictures of closed, multi-layered canopies. Even in the cases where vegetation needs to be cut for biomass quantification, the technique described herein represents a significant improvement in the speed of sample evaluation.

The results also show that the method presented in this work can be readily applied to classification of other colours besides green. Furthermore, higher colour resolution formats and more complicated classification regions on the chromaticity diagram can help to determine more precisely the range of colour associated with a given type of vegetation. However, it has to be remembered that application of this method is equivalent to discarding the information of the intensity or brightness. The fact that a high linearity was obtained from a single picture calibration shows that the method is not particularly sensitive to illumination conditions.

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