MEASURING GRASS YIELD BY NON-DESTRUCTIVE METHODS: A REVIEW

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ABSTRACT

Accurate assessment of forage mass in pastures is a key to budgeting forage in grazing systems. Different non-destructive techniques to measuring pasture yield are commented. The methods compared include visual estimations, manual and electronic pasture meters and remote sensing. All methods are associated with a moderate to high error, showing that some indirect methods of yield estimation are appropriate under certain conditions. In general terms, no method was found as the most appropriate because many factors as climate variations, soil characteristics, plant phenology, pasture management and species composition must be used to make local calibrations from a general model. Best results were found modifying general methods under local calibrations and under local conditions. In order to give farmers the best method to manage adequately their own grazing systems, researches must select the most suitable technique considering the scale of operation, the desired accuracy and the resources available.

Keywords: forage mass, estimation methods, pasture yield, non-destructive measuring.

INTRODUCTION

Vegetation is measured for a wide range of purposes, such as: description in terms of botanical composition, ground cover, amount of dry matter, quality of dry matter, biological alters in relation with climate changes, and for determining its capacity to provide feed of livestock (Mannetje, 2000a and 2000b). During the past 70 years, many indirect non-destructive methods for quickly estimation of forage mass have been proposed and evaluated (Catchpole and Wheeler, 1992; Lucas and Thomson, 1994). Traditionally, estimates from manually or mechanically clipped quadrats have been used to estimate herbage mass. Many authors agree that clipping provide accurate measures of biomass, however it is expensive, time intensive and may require numerous samples to obtain reliable pasture estimates (Brummer *et al*., 1994). Moreover, the time and labour required constrain the number of samples that can be collected realistically. Alternative to clipping, sampling procedure methods that use double sampling techniques are commonly used by researchers to increase the precision of estimations and minimise the amount of work (Sanderson *et al*., 2001). These methods function by developing a regression relationship of standing crop to predictive values, such as plant height, leaf area, vegetation density, canopy, age, cover, visual obstruction or remote sensing data (Cochran, 1977). However such estimations usually are associated with a moderate to high experimental error, because relationships between production and pasture variables depends on numerous factors that can interact mutually. The accuracy of estimations can be affected by many factors such: the density and growth state of plants (Mosquera *et al*., 1991), the season (Phillips and Clarke, 1971; Powell, 1974; Vartha and Matches, 1977; Bransby *et al*., 1977), species composition of the meadow (Castle, 1976) and management (Powell, 1974). Traditional methods *as visualestimation* (Baars and Dyson, 1981), are satisfactory for general grassland inventories, but, as reported by Tucker (1980), it suffers from variations among observers and is not a quantitative method. A variety of methods that use more sophisticated instruments have been developed during the past 50 years, some of them have been adapted for its commercial use. This paper considers the application of different techniques that may be useful in measuring forage production or standing crop.

IN SITU MEASUREMENT INSTRUMENTS

Manual instruments

The most simple instruments are the *pasture ruler* and the *plate disc*. Pasture ruler relies on a positive relationship between forage yield and uncompressed canopy height. A widely used implement in Europe is the *sward stick* (Barthram, 1986), which measures plant height rather than compressed sward height. It employs a 2 × 1 cm clear window that is lowered vertically on a shaft until its base touches the vegetation. The height contact above the ground is recorded in 0.5 cm bands. However canopy height can be difficult to measure due to the subjectivity associated with which plant or plan parts should be considered to form a mean height measure (Heady, 1957), so researchers have been added several types of discs or plates to the rule to incorporate an area dimension to the measurement. Plate discs consist in grass meters with a light, horizontal plate (called 'weighted disc', 'rising plate', 'drop-disc' or 'pasture disc' in bibliography) of about 0.3 x 0.3 m that can slide up or down a central, vertical and graduated stem (Frame, 1993). Several authors suggested modifications from this design as the substitution of the metal plate by other materials such an acrylic and transparent plastic with some markers or holes (Rayburn and Rayburn, 1998, Fig. 1). These holes allow the use of the plate as a squared paper for estimating ground cover of for measuring the occurrence of forage species under the sampling area.

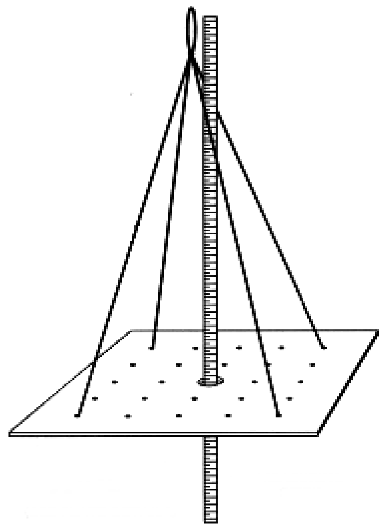

Fig. 1. (From Rayburn and Rayburn, 1998)). Scheme of the weighted disk meter.

A method called *visual obstruction* was proposed in 1970 by Robel *et al*., (1970a, 1970b). A striped pole often called the Robel pole measures the lowest point of the pole not visually obstructed by vegetation when placed vertically in a sward. Numerous transects are walked and the observer stops at intervals, sets the pole vertically in the vegetation, steps back 4 m from the pole, and reads the last visible number toward the lower end of the pole at three heights (0.5, 0.8 and 1.0 m). Such observations are made at the four cardinal directions around the pole. Michalk and Herbert (1977) compared this method with hand-clipping and ground cover measures, and obtained a good correlation between height and herbage mass, with a r^2 of 0.81. Harmoney *et al*., (1997) found this technique the most suitable in

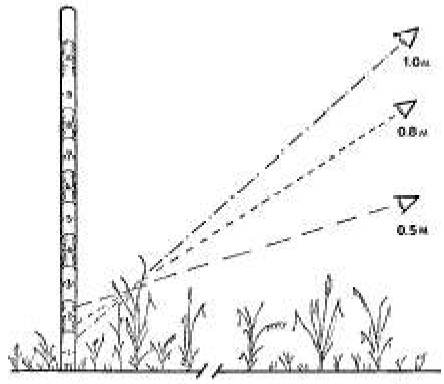

Fig. 2. (From Robel *et al*., 1970). Diagram of Robel Pole. Readings are taken at each of three heights 2, 3 and 4 m from the pole.

comparison with rising plate meter, LAI analyser and canopy height stick, with a r^2 = 0.63. Similar conclusion were found by Ganguli *et al*. (2000) in the same comparison, with a r^2 = 0.87. Ackerman *et al*., (1999) obtained a lower value (r^2 = 0.59) in a two-year trial, and concluded in that this technique has potential for practical use. Benkovi *et al*., (2000) found a r^2 value of 0.88, and Vermeire *et al*. (2001) found a r^2 = 0.90. As can be seen, all papers reviewed consider visual obstruction technique as a good method for non-destructively estimating. However, there are some considerations about the use of this technique: as shown by Heady (1957), some factors difficult exact measures of pasture height: the highest point may be difficult to identify when plants are lodging or dropping, when the point is the tip of an structure, and when several parts are nearly the same height. The second consideration is that no many references exist in the literature, and as reported by Ganguli *et al*. (2000) investigations on the performance of this method in different vegetation types are limited.

Electronic instruments

More complex electronic instruments as the *electronic capacitance meter*, first reported by Fletcher and Robinson (1956) and *sonic sward stick* (Hutchings *et al*., 1990) have been developed to improve speed and precision of sampling. The sonic sward stick calculates sward height from the flight time of an ultrasonic pulse bounced off the sward surface. Electronic capacitance meter uses a single rod probe and an electronic system that accumulates the readings from a number of sampling sites within a pasture plot (Vickery *et al*., 1980; Vickery and Nicol, 1982). The reading-system relies on differences in dielectric constants between air and herbage and it measures the capacitance of the air-herbage mixture, responding mainly to the surface area of the foliage (Sanderson *et al*., 2001). A variety of capacitance meters have been built under this principle and incorporating various modifications (Campbell *et al*., 1962; Hyde and Lawrence, 1964; Alcock, 1964; Downling *et al*., 1965; Johns *et al*., 1965; Morse, 1967; Terry *et al*., 1981; Van Dyne *et al*., 1968; Kreil and Matschke, 1968; Jones and Haydock, 1970; Johns, 1972; Murphy *et al*., 1995). However and as reported by Murphy *et al*., (1995), readings are affected by water in vegetation, including litter, and is not an accurate method during or immediately following rainfall. Commercial instruments often come with standard equations, and the precision of this instrument depends on the adjustment on these calibration equations. Many studies have shown that the use of indirect methods to obtain a measure of pasture biomass, using this standardised equations are not representative in different conditions and situations, because of variations in pastures, management and climate (see Frame, 1993). Dowdeswell (1998) reported a poor relationship between yield estimated with a rising plate meter using New-Zealand equations and measured yield. Sanderson *et al*., (2001), obtained low correlation coefficients with pasture ruler, rising plate meter and capacitance meter on cool season grass-legume pastures in three dairy farms of north east USA (Pennsylvania, Maryland and Virginia); the three trials used commercial calibrations made in New-Zealand. These authors suggested that an error level upper from 10% could be statistically acceptable, but economically inaccurate. Given the inherent spatial and temporal variability of pastures, it may be difficult for a producer to achieve an error lower than proposed 10%, however some authors found that local calibrations can reduce error to about 10% (Rayburn and Rayburn, 1998; Unruh and Fick, 1998).

Many experiments which pre and post-grazing estimations were compared, showed that post-grazing measures where poorly correlated with estimations, specially when the residue is very short, due to soil surface roughness combined with the weight of rising-plate, which was too heavy to be supported by the short stubble (Murphy *et al*., 1995). An added problem to post-grazing estimations is the effect of trampled herbage mass, which can affect the calibrations of instruments. Stockdale (1984) suggested that the aspect of trampling is the major factor that may preclude the rising-plate meter from general use in dairy cattle research. If the herbage is evenly trampled, there would not be a problem with either meter, however dairy cows trample a sward unevenly. Stockdale and Kelly (1984) concluded that cutting quadrats was the best way to estimate post-grazing herbage mass when it is unevenly trampled. A possible solution to this problem is to estimate the proportion of the sward that is trampled and apply different regressions to each proportion. In the other hand, as plant density increases in local areas, the number of stems in a given area increases, this higher density may result in a sward which would provide more local resistance to an object which is allowed to settle onto it.

Experimental error due to the sampling method also constitutes an important source of variation. In this way, the sensibility of an instrument varies with the spatial work scale, the sampling area and the *modus operandi* (Hutchings, 1991). Aiken and Bransby (1992) observed significative differences in measurements of the same grass bulk measured by four different observers, as in the selection of the representative sampling area too, showing that the observer constitutes itself another source of variation. Variability between observers were also reported by Earle and McGowan (1979), who suggested that significative differences between observers recommend that meter readings on calibration and in pasture measurements should be taken by the same operator.

Accuracy of calibration equations

According with Rayburn (1997) the logical model for rotationally grazed pastures, grazed to a short residual height, is a linear equation that passes through the origin. Under continuously grazed pastures where a thatch build-up occurs, a regression model using an Y intercept is most appropriate. In Table 1 is given a comparison between regression models obtained from several author in various types of pasture meters. Usually the more used regression model is linear, however some works with plate meters showed an exponential response in highest values of disk meter values (Bransby *et al*., 1977; Baker *et al*., 1981; Li *et al*., 1998). Such mathematical trend have been observed too in capacitance meters (Terry *et al*., 1981; Stockdale and Kelly, 1984; Greathead *et al*., 1987; Vickery *et al*., 1980). Data given in Table 1 show that best mean coefficient of determination (r^2) were found in manual instruments, from higher value of visual obstruction technique (r^2 = 0.78), followed by plate meters (r^2 = 0.74), pasture rulers (r^2 = 0.72) and sward sticks (r^2 = 0.69). worst correlations were found in electronic meters, from capacitance meters (r^2 = 0.68), to canopy analyzer (r^2 = 0.78), but this last meter only have two data.

Double-sampling techniques are applied to calibrate non-destructive devices by a regression model. The precision of a given estimation technique may be evaluated either by reference to the residual standard deviation (RSD) of a calibration equation, either by comparing the variance of a sample estimate obtained non-destructively with that from clipping (Griggs and Stringer, 1988). The variance of a sample estimated obtained by double-sampling is given by Cochran (1977):

$$S^2(\hat{Y}) = \frac{S_{yx}{}^2}{n} + \frac{S_y{}^2 - S_{yx}{}^2}{n'} - \frac{S_y{}^2}{N}$$

where S^2_{yx} is the residual mean square from calibration, S^2_y is the variance of herbage mass observations in the calibration set, n is the number of direct (clipped) observations in the calibration set, n' is the number of total indirect (by a device meter) in calibration plus prediction sets, and N is the population of possible indirect observations in the sampled area (e.g. five 0.2 m^2 sampling units within a 1 m^2 area, as provided by Griggs and Stringer, 1988).

Bransby *et al*., (1977) proposed the RSD of the regression of dry matter yield Y on meter readings X as:

$$RSD = \frac{\sqrt{\sum(Y-\overline{Y})^2 - \dfrac{\left[\sum(X-\overline{X})(Y-\overline{Y})\right]^2}{\sum(X-\overline{X})^2}}}{n-2}$$

where n is the number of paired observations made to establish the overall regression equation. Another similar formulas where given by McIntyre (1978) simplified by Michell (1982).

Meter	*Model*	*R^2*	*Period*	*Source*	*Units*
Canopy analyzer	Y = 147 + 847.26 X	0.32	Annual	Harmoney et al., 1997	kg/ha - units
	Y = 369.3 + 2517.4 X	0.67	Summer	Ganguli et al., 2000	kg/ha - units
Capacitance meter	Y = 1289 + 28 X	0.89	Annual	Gonzalez et al., 1990	kg/ha - units
	Y = 330 + 0.617 X	0.25	Annual	O'Sullivan, 2002	kg/ha - cm
	Y = 901 + 0.3 4 X	0.14	Annual	Sanderson et al., 2001	kg/ha - units
	ln (Y) = 0.718 + 0.763 X	0.72	Annual	Terry et al., 1981	g/0.186 m^2 - units
	ln (Y) = 14.62 + 0.54 X	0.59	Annual	Terry et al., 1981	g/0.186 m^2 - units
	$Y = 5410.8 - 5512.4\ e^{-006X}$	0.86	Annual	Vickery et al., 1980	kg/ha - units
	Y = 9.9 X + 600	0.86	Spring	L'Huillier, 1988	kg/ha - cm
	Y = 1209 + 14 X	0.84	Spring	Michell and Large, 1983	kg/ha - units
	Y = -313.6 + 0.9 X (pregrazing)	0.42	Spring	Murphy et al., 1995	kg/ha - cm
	Y = -369.1 + 0.89 X (postgrazing)	0.13	Spring	Murphy et al., 1995	kg/ha - cm
	ln (Y) = 0.16 + 0.918 ln (X)	0.82	Spring	Terry et al., 1981	g/0.186 m^2 - units
	Y = 1200 + 9.5 X	0.86	Spring-summer	L'Huillier, 1988	kg/ha - cm
	Y = 1240 + 13.8 X	0.86	Summer	L'Huillier, 1988	kg/ha - cm
	Y = 1314 + 20.3 X	0.83	Summer	Michell and Large, 1983	kg/ha - units
	ln (Y) = 0.126 + 0.837 ln (X)	0.67	Summer	Terry et al., 1981	g/0.186 m^2 - units
	Y = 1020 + 12.7 X	0.86	Summer-autumn	L'Huillier, 1988	kg/ha - cm
	Y = 990 + 10.4 X	0.86	Autumn	L'Huillier, 1988	kg/ha - cm
	ln (Y) = 0.363 + 0.911 ln (X)	0.82	Winter	Terry et al., 1981	g/0.186 m^2 - units
Pasture ruler	Y = 37 + 21.7 X	0.86	Annual	Gonzalez et al., 1990	kg/ha - mm
	Y = 876 + 0.29 X	0.11	Annual	Sanderson et al., 2001	kg/ha - cm
	Y = -31.85 + 0,073 X	0,72	Spring	Carton et al., 1989	kg/ha - mm
	Y = 590 + 120 X	0.81	Spring	L'Huillier, 1988	kg/ha - cm
	Y = 1340 + 70 X	0.81	Spring-summer	L'Huillier, 1988	kg/ha - cm
	Y = 1340 + 172 X	0.81	Summer	L'Huillier, 1988	kg/ha - cm
	Y = 810 + 195 X	0.81	Summer-autumn	L'Huillier, 1988	kg/ha - cm
	Y = 400 + 300 X	0.81	Autumn	L'Huillier, 1988	kg/ha - cm
Plate meter	Y = 762 + 155 X	0.97	Annual	Earle and McGowan, 1979	kg/ha - cm
	Y = 282 + 29.3 X	0.91	Annual	Gonzalez et al., 1990	kg/ha - mm
	Y = 68.11 + 202.9 X	0.59	Annual	Harmoney et al., 1997	kg/ha - cm
	Y = 36 + 149 X	0,78	Annual	Hoden et al., 1991	kg/ha - cm
	Y = -507 + 31 X	0,51	Annual	Mayne et al., 1988	kg/ha - cm
	Y = -1061 + 35 X	0,48	Annual	Mayne et al., 1988	kg/ha - cm
	Y = 278 + 0.48 X	0.31	Annual	Sanderson et al., 2001	kg/ha - cm
	Y = -36.34 + 140.63 X	0.76	Annual	Mosquera et al., 1991	kg/ha - cm
	$Y = 10.26 + 128.18\ +0.6\ X^2$	0.76	Annual	Mosquera et al., 1991	kg/ha - cm
	Y = 362 + 225 X	0.71	Annual	O'Sullivan, 2002	kg/ha - cm
	Y = 3 + 452 X	0.52	Annual	Rayburn and Rayburn, 1998	kg/ha - cm
	Y = 88.01 + 13.8 X	0.76	Spring	Bransby et al., 1977	kg/ha - cm
	Y = 640 + 125 X	0.84	Spring	L'Huillier, 1988	kg/ha - cm
	Y = 371 + 18 X	0,52	Spring	Mayne et al., 1988	kg/ha - cm
	Y = 4.3 + 6.24 X	0.67	Spring	Michalk and Herbert, 1977	g/m2 - cm
	Y = 1011 + 271 X	0.96	Spring	Michell and Large, 1983	kg/ha - cm
	Y = 8.75 + 140.46 X	0.74	Spring	Mosquera et al., 1991	kg/ha - cm
	$Y = 16.62 + 134.32\ X\ + 0.27\ X^2$	0.74	Spring	Mosquera et al., 1991	kg/ha - cm
	Y = 392.9 + 317.8 X (pregrazing)	0.52	Spring	Murphy et al., 1995	kg/ha - cm
	Y = 1237.6 + 53.4 X (postgrazing)	0.00	Spring	Murphy et al., 1995	kg/ha - cm
	Y = -4.1 + 1.01 X	0.94	Spring-summer	Griggs and Stringer, 1988	g/m2 - mm
	Y = 990 + 130 X	0.84	Spring-summer	L'Huillier, 1988	kg/ha - cm
	Y = 14 + 22 X	0,72	Sprng	Mayne et al., 1988	kg/ha - cm
	Y = -188 + 154 X	0.77	Summer	Bransby et al., 1977	kg/ha - cm
	Y = -515.44 + 328.39 X	0.83	Summer	Ganguli et al., 2000	kg/ha - cm
	Y = 1480 + 165 X	0.84	Summer	L'Huillier, 1988	kg/ha - cm
	Y = 3102 + 61 X	0,79	Summer	Mayne et al., 1988	kg/ha - cm
	Y = -175 + 47 X	0,53	Summer	Mayne et al., 1988	kg/ha - cm
	Y = 925 + 385 X	0.90	Summer	Michell and Large, 1983	kg/ha - cm
	Y = 1180 + 159 X	0.84	Summer-autumn	L'Huillier, 1988	kg/ha - cm
	Y = -942 +33 X	0,62	Summer-autumn	Mayne et al., 1988	kg/ha - cm
	Y = -844 + 32 X	0,39	Summer-autumn	Mayne et al., 1988	kg/ha - cm
	$\ln (Y) = 5.65 + 0.52\ X\ - 0.02\ X^2$	0.81	Summer-autumn	O'Sullivan et al., 1987	kg/ha - mm
	Y = 50.4 + 385.8 X	0.76	Summer-autumn	O'Sullivan et al., 1987	kg/ha - mm
	Y = -1393 +239 X	0.62	Autumn	Bransby et al., 1977	kg/ha - cm
	Y = 970 + 157 X	0.84	Autumn	L'Huillier, 1988	kg/ha - cm
	Y = -143 + 209 X	0.88	Winter	Bransby et al., 1977	kg/ha - cm
Sward stick	Y = -6.4 + 15.1 X	0.91	Annual	Duru and Bossuet, 1992	g/m^2 - cm
	Y = 62.6 + 11.9 X	0.78	Annual	Duru and Bossuet, 1992	g/m^2 - cm
	Y = 485.01 + 56.57 X	0.55	Annual	Harmoney et al., 1997	kg/ha - cm
	Y = -22.08 + 799.93 X	0.78	Annual	Mosquera et al., 1991	kg/ha - cm
	$Y = 100.21 + 44.17\ X\ +1.7\ X^2$	0.80	Annual	Mosquera et al., 1991	kg/ha - cm
	Y = -117 + 167.7 X	0.60	Annual	O'Sullivan, 2002	kg/ha - cm
	Y = 48.27 + 82.58 X	0.81	Spring	Mosquera et al., 1991	kg/ha - cm
	$Y = 98.08 + 44.28\ X + 1.69\ X^2$	0.83	Spring	Mosquera et al., 1991	kg/ha - cm
	Y = 398.1 + 71.6 X (pregrazing)	0.49	Spring	Murphy et al., 1995	kg/ha - cm
	Y = 931.8 + 79.9 X (postgrazing)	0.10	Spring	Murphy et al., 1995	kg/ha - cm
	Y = 7.5 + 0.78 X	0.80	Spring-summer	Griggs and Stringer, 1988	g/m2 - mm
Visual obstruction	Y = 1093.3 + 91.1X	0.63	Annual	Harmoney et al., 1997	kg/ha - cm
	Y = 19 + 113 X	0.94	Annual	Robel et al., 1970	g/m^2 - dm
	Y = 14.05 + 4.02 X	0.66	Spring	Michalk and Herbert, 1977	g/m2 - cm
	Y = -819.47 + 256.62 X	0.87	Summer	Ganguli et al., 2000	kg/ha - cm

Table 1. Best regression models found in bibliography for forage mass estimation in most used measurement techniques. Meters are grouped in six categories by type of technique used.

REMOTE ESTIMATION SYSTEMS

Modern information technologies such as *remote sensing* and *geographical information systems* are being used increasingly as tools to assist in grassland resource inventory, modelling and forecasting to support decision-making. The principle of remote estimation is based on the spectral radiance reflected by plant canopy. Radiation reflectance is affected by leaf area index (LAI), which is related to vegetation cover, which may be used as a measure of total forage biomass. LAI can be estimated by measuring light transmission within stands by a photometer. Numerous commercially

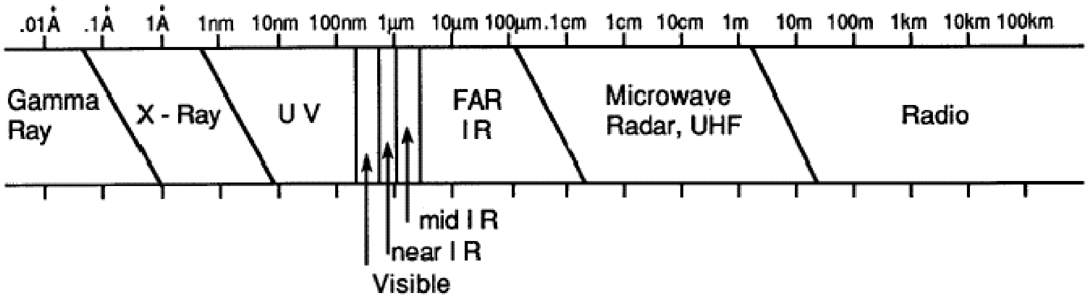

Fig. 3: (From Tueller, 1989). Scheme of regions of electronic spectrum that have potential remote sensing applications for biomass estimations.

available instruments, such as Decagon ceptometer or LI-COR LAI-2000 plant canopy analyser (LI-COR 1992, Deblonde and Penner 1994) are used to indirectly estimate LAI. Spectral estimations use two wavelengths regions (Fig. 3): the red (0.60-0.70 μm) and the near infrared (0.75-1.00 μm). The first region corresponds to the *in vivo* red region of chlorophyll absorption and is inversely related to the chlorophyll density. The second region is related to the fragment of spectrum where reflectance is proportional to the green leaf density. Vegetation indices derived from remote sensing data have emerged as an important tool to quantify vegetation biomass, as intermediaries in the assessment of LAI, percent green cover, green biomass, and fraction of absorbed photosinthetically active radiation (fAPAR). Many factors can affect reflectance in any given waveband, such: senescence of the plant (Tucker, 1978), soil background (Heilman and Boyd, 1986), species composition (Asrar *et al.*, 1986), fertiliser status (Vickery and hedges, 1987), nitrogen contents (Filella *et al.*, 1995) and presence of trees in large samples (Williamson, 1990). Another factors non-dependent of plants can influence the received signals, Tueller, (1987) has reported that in rangelands, especially arid and semi-arid rangelands, soil background conditions and shadows often influence the signal received by a multispectral scanner, so frequently a pre-processing procedure of remote sensing data often has to be made to improve quality of correlation coefficients (Williamson, 1990). Because the large amount of factors affecting spectral reflectance, the use of vegetation indices, less dependent of external factors, reduce measurement variability due to soil type, sunlight intensity, angle of sunlight incidence (Olson and Cochran, 1998) and eliminate noise produced by these and other cited factors. Most used vegetation indices are normalised differenced vegetation indices (NDVI) and simple ratio index (SR). First index used was SR (Jordan, 1969), formed by dividing the NIR response by the corresponding 'red' band output, ($SR = X_{nir} / X_{red}$) where X can be digital counts, at- satellite radiances, top of the atmosphere apparent reflectances, land leaving surface radiances, surface reflectances, or hemispherical spectral albedos. However, for densely vegetated areas, the amount of red light reflected approaches very small values and this ratio, consequently, increases without bounds. Deering (1978) normalised this ratio from -1 to +1, by rationing the difference between the NIR and red bands by their sum ($NDVI = [X_{nir} - X_{red}] / [X_{nir} + X_{red}]$). For terrestrial targets the lower boundary became approximately zero and the upper boundary approximately 0.80. Another commonly used indices are perpendicular vegetation index (PVI, Richardson and Wiegand, 1977) and soil adjusted vegetation index (SAVI, Huete, 1988; Qi *et al*., 1994). An excellent review of vegetation indices is reported by Jackson and Huete (1991) and Thenkabail *et al*. (2000). Many studies have shown vegetation indices to be related to leaf area index (LAI), green biomass, percent green cover and fAPAR (Asrar *et al*., 1984; Goward and Huemmrich, 1992; Sellers, 1985; Running and Nemani, 1988; Curran, 1980). Relationships between fAPAR and NDVI have been shown to be linear (Pinter, 1993; Begue, 1993; Wiegand *et al*., 1991; Daughtry *et al*., 1992), in contrast with the non-linear relationship with LAI (Asrar *et al*., 1984; King and Barthram, 1986; Aparicio *et al*., 2000), because the signal saturates as the LAI value becomes higher than 2 o 3, and as reported by Laca and Lemaire (2000) estimation of LAI has to be restricted to periods of leaf area expansion just after sowing or severe defoliation. Other studies have shown the NDVI to be related to carbon-fixation, canopy resistance, and potential evapotranspiration allowing its use as input to models of biogeochemical cycles (Raich and Schlesinger, 1992; Fung *et al*., 1987; Sellers, 1985; Running *et al*., 1989; Running, 1990).

Imaging spectrometers (called hyperespectral scanners) may provide data at several scales of observation: either at surface level by mounting teledetection systems at land surface, either by airborne systems mounted in aircraft, which more typical are Airborne Visible-infrared Imaging Spectrometer (AVIRIS) and Compact Airborne Spectrographic Imager (CASI). These systems can provide reflectance measures in up to 256 wavelength intervals at 4m/pixel, providing both very high spatial and spectral resolutions. In a spatial scale, Earth Observation Satellites carry broad-waveband sensors shown in Table 2. In this table is given a scheme of satellite systems with are commonly used in grassland remote sensing: Landsat Enhanced Thematic Mapper (ETM+) and Thematic Mapper (TM), Multispectral scanner (MSS), Le Systeme pour l'observation de la terre (SPOT), the Advanced Very High Resolution Radiometer (AVHRR) of the polar orbiting series of NOAA (National Oceanic and Atmospheric Administration) and the Indian Remote Sensing (IRS) and Linear Imaging Self-Scanning (LISS). These sensors have provided information in many studies, the most developed applications concern the land use and the vegetation classification, where thematic pixels are chosen as reference classes, and all the other pixels are sorted in these classes. Remote sensing from satellite data have provided accurate estimates of drought monitoring (Hutchinson, 1991; Peters *et al*., 1991), estimation of primary productivity in large regions (Tucker *et al*., 1985; Prince 1991), biophysical and yield characteristics of agricultural crops (Asner *et al*., 2000; Carter, 1997; Gong *et al*., 1995; Richardson *et al*., 1992; Shaw *et al*., 1998; Wiegand *et al*., 1992), crop moisture variations (Peñuelas *et al*., 1993 and 1995), leaf pigments (Blackburn, 1999; Blackburn and Steele, 1999), characterising natural vegetation (Friedl *et al*., 1994; Thenkabail, 1999), assessing crop or vegetation stress (Blackburn, 1998; Dawson and Curran, 1998), highlighting nitrogen or organic matter deficiencies (McGwire *et al*., 2000), detection of crop phenology (Badhwar and Henderson, 1981), etc.

NAME	Pixel size (m)	Image size (km)	Spectral/radiometric resolution	Lifetime
Landsat MSS	80	185	Vg, Vr, NIR, NIR (6-7 bit)	1972-1997
Landsat TM	30º	185	Vb, Vg, Vr, NIR, MIR, MIR, TIR (8 bit)	1984-present
SPOT XS	20	60	Vg, Vr, NIR (8 bit)	1986-present
SPOT PAN	10	60	V (8 bit)	1986-present
NOAA AVHRR	1100	2700	Vr, NIR, MIR, TIR, TIR (10 bit)	1978-present
IRS LISS	25,36,72	142	Vb, Vg, Vr, NIR (7 bit)	1988-present
IRS WIFS	180	774	Vr, NIR, SIR (7 bit)	1995-present
IRS PAN	5	70	V (6 bit)	1995-present

Table 2. (Modified from Roderick *et al*., 2000). Characteristics of some earth resource satellite sensors. Bands are: V = visible, with subscripts (b, g, r) to signify which part of the visible spectrum; NIR = near infrared; MIR = mid infrared; TIR = thermal infrared; SIR = short-wave infrared (0.7–3.0 μm).

However, as reported by Roderick *et al*., (2000) there are some problems of spatial resolution, for example pixel size provided for NOAA-AVHRR (1100 m) is not suitable at landscape and paddock scales and more reduced dimension has to be used (Bastin *et al*., 1995). It is expected that new satellite systems such as Earth Observing System (EOS) and Earth Observing-1 (EO-1) carrying hyperspectral scanners will open researches a new phase in terrestrial applications.

Some interesting applications of remote sensing data are to integrate multispectral data into quantitative models to estimate growth. For example Maas *et al*. (1992) and Moran *et al.* (1995) used remotely sensed estimates of LAI and evapotranspiration as inputs to a single alfalfa growth model. Lobel *et al*. (2001) combined multi-date Landsat ETM+ imagery with a field-based model of crop production, obtaining good correlation between predicted and real yield (r^2 = 0.82). Others similar studies are increasing in literature with the apparition of new data and new technologies to develop or to correct some growth models (Mougin *et al*., 1995; Carbone *et al*., 1996). Another interesting application is the use of remote sensing data to obtain multi-temporal series over time in grasslands, which have direct applications in study of global climatic changes. With the recent projects of development of new satellites in a near future (Aplin *et al*., 1997) resolution could increase to 1-5 m, offering vastly improved spatial resolution. But as reported by Roderick *et al*. (2000) best applications come from the development of a global broad-band communication network that may improve global grassland management.

CONCLUSIONS

Many works has shown that non-destructive biomass estimations in grasslands are statistically acceptable when are present both choice of an accurate system and the development of a correct model. The choice depends of the work scale, resources available and precision required. Remote sensing data has shown a potential use but not an exact management of agricultural systems in past years, due to restrictions derived from spatial resolution and technical limitations. Modern systems and information accessible by networks and international programs are increasing researches possibilities to provide farmers an improved management of grazing systems

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