Precision Agric
DOI 10.1007/s11119-011-9227-4

Calibration of a capacitance probe for measurement and mapping of dry matter yield in Mediterranean pastures

João M. Serrano · José O. Peça · J. Marques da Silva · Shakib Shahidian

Abstract The main objective of this study was to calibrate a commercial capacitance probe for measuring pasture dry matter yields under Mediterranean conditions. The standard method of assessing pasture biomass is based on cutting all the forage within a specified area and requires great effort and expense to collect enough samples to accurately represent a pasture. The field tests were carried out in 2007, 2008 and 2009 on different dates (phenological stages), and on five dairy farms, representing typical pastures in the region (grasses; legumes; and bio-diverse flora, mixture of grasses, legumes and others species). The linear regression techniques used in 2007 to relate the weight of the herbage (direct measurements) to the meter reading of capacitance (indirect measurements) led to high regression coefficients in grasses ($R^2 = 0.90$; $P < 0.01$) and heterogeneous botanical composition ($R^2 = 0.87$; $P < 0.001$) and moderate regression coefficient in legumes species ($R^2 = 0.48$; $P < 0.05$). The validation of the calibration equations in 2008 and 2009 in two sites showed RSME values of 130 kg ha^{-1} in heterogeneous botanical composition and 456 kg ha^{-1} in legumes. The results indicated that the capacitance probe together with a GPS receiver might support site-specific management of pastures which would be useful in large areas.

Keywords Calibration · Capacitance probe · Pastures

Introduction

The cost of precision farming techniques can only be justified if the variability of a site and differences in yield potential warrant it (King et al. 2005). The application of sensor techniques to evaluate the existing variability is difficult on permanent grassland with diverse species, plant spacing, morphology and colour. In addition to different vegetation types, the annual variations of flora introduce significant variability and uncertainty into standardized sensing techniques on permanent grassland (Currie et al. 1987; Schellberg et al. 2008). Furthermore, the situation becomes more complicated when grazing animals

J. M. Serrano (✉) · J. O. Peça · J. Marques da Silva · S. Shahidian
ICAAM, Rural Engineering Department, University of Évora, 7000 Évora, Portugal
e-mail: jmrs@uevora.pt

Published online: 11 May 2011

are involved, due to dynamic interactions between plants and animals (Ogura and Hirata 2001). In contrast to equal defoliation of the sward for silage and hay, grazing animals create specific spatial patterns of sward biomass, which change throughout utilization, and have a considerable effect on the spatial heterogeneity of the grassland field (Rook et al. 2004). To deepen an understanding of such interactions, it is necessary to know the determinants of choice of grazing locations and intensities of selective grazing by animals (Ogura and Hirata 2001). Understanding how spatial and temporal variability of animal, forage, soil and landscape features affect grazing behaviour and forage utilization provides potential to modify pasture management, improve efficiency of utilization, and maximize profits (Turner et al. 2000). Recent advances in global positioning system (GPS) technology have allowed the development of lightweight GPS collar receivers suitable for monitoring animal position, to assess animal behaviour characteristics and pasture utilization. In the 1990s, the University of Kentucky began using GPS collars on cattle to track their position with the goal of incorporating this information into cattle management practices (Agouridis et al. 2004). Barbari et al. (2006) showed that research methodologies which combine global position system information with geographical information system analyses have an effective potential to support studies on livestock behaviour in pastures.

Grazing management and planning of animal production systems from pastures are essentially based on estimated herbage mass, production and accumulation rates (Virkajarvi 1999). The methods mentioned in the literature for evaluating the forage in a pasture are mainly grouped in direct methods, such as cutting the forage in a sample area of the pasture, and indirect methods, which do not harm the pasture and are faster, requiring less man power. The standard method of assessing pasture and forage mass is based on cutting all the forage in an area of the pasture that is being sampled (Cauduro et al. 2006). Systematic manual plant sampling has been used to analyse spatial distribution of dry matter yield and plant nutrient concentration and to predict its variability on grassland (Bailey et al. 2001). This method requires great effort and expense to collect enough samples to accurately represent a pasture (Sharrow 1984; Hanna et al. 1999; Ganguli et al. 2000). Similar problems occur during the evaluation of large-size pasture yields, which require a high number of destructive samples to obtain sufficient accuracy of the estimate (Franca et al. 2003). Farmers are not willing to make this effort for day-to-day management of pastures (Virkajarvi 1999; Sanderson et al. 2001). Therefore, other techniques, useful over large areas, are required to clarify yield variability and implement more contemporary production strategies such as precision farming or site-specific management.

During the past 70 years, many indirect methods have been evaluated, from simple rulers to sophisticated electronic meters. Any of these methods is expected to provide a good representation of the conditions or state of the pasture, with low operating costs and good precision (Zanine et al. 2006). Other indirect sensing techniques, such as optical (Hanna et al. 1999) and ultrasound (Hutchings 1991) in situ and on-the-go pasture meters and even remote sensing are an actual possibility. Active optical plant radiometric sensors, that measure the visible and near-infrared (NIR) radiation reflected from the vegetation canopy, offer the potential of quantifying biomass over large areas with high spatial resolution by remote-sensing techniques at ground level (Hanna et al. 1999).

Some methods, including the electronic capacitance meter, have been adapted for commercial use. The interest in this evaluation process remains current as each pasture is a different ecosystem, with specific characteristics, which vary with different vegetative states of plants, according to type of grazing management. This interest has been demonstrated in different studies such as those by Stockdale and Kelly (1984), Hirata (2000), Silva and Cunha (2003), Zanine et al. (2006) and Cauduro et al. (2006).

Commercially available meters come with factory calibrations; however, accuracy and precision of these equations have not been evaluated for Mediterranean pasture conditions. Several previous studies of double-sampling techniques have shown that these techniques require frequent calibration and that universal equations for estimating pasture mass have not been useful because of variations in pastures, management and climate (Virkajarvi 1999; Sanderson et al. 2001; Zanine et al. 2006). Since the relationship between herbage mass and corrected meter reading of an electronic capacitance probe is known to vary with such factors as sward type, growth season (developmental stage), herbage moisture content and ratio of green to dead material and is also expected to vary with grazing, calibration equations must be developed separately for individual measurement occasions (Hirata 2000). Calibration equations between capacitance and dry matter yield are known to vary between sites due to differences between plant species, plant water content, grazing, trampling of vegetation, phenological stage and accuracy of dry matter regression (Reese et al. 1980; Karl and Nicholson 1987; Aiken and Bransby 1992).

The main objective of this study was to calibrate a commercial capacitance probe for measuring pasture dry matter yields under Mediterranean conditions.

Materials and methods

Equipment

The following equipment was used in the field experiments:

- Cutting shears and plastic bags for storing the pasture samples;
- Enclosure cages, with a 1 m^2 area, to protect the pasture from grazing, and allow evaluation of pasture productivity;
- Metallic rim with a 1 m^2 area to clearly mark the field and the reference area of the samples;
- Trimble RTK/PP 4700 survey grade GPS (global positioning system) receiver, manufactured by TRIMBLE Navigation Limited, USA;
- Grassmaster II—electronic capacitance probe, manufactured by Novel Ways Electronic, Hamilton, New Zealand.

Co-ordinates measurement

The Trimble RTK 4700 survey grade receiver works under differential mode (dGPS): uses two receivers, one as a fixed base station placed on known locations on the ground, in the boundary of the experimental field, and the other as a moving receiver, designated as rover. Correction data is transmitted from the base station to the rover in real-time using a radio. The dGPS survey grade receiver was used to carry out all the topographical surveys. The horizontal and vertical errors of this system were less than 0.02 and 0.04 m, respectively.

Capacitance instrument

Capacitance instruments are generally composed of an electronic circuit which generates a signal of a certain frequency, and then carries out a measurement of the capacitance of the air-herbage mixture (Currie et al. 1987).

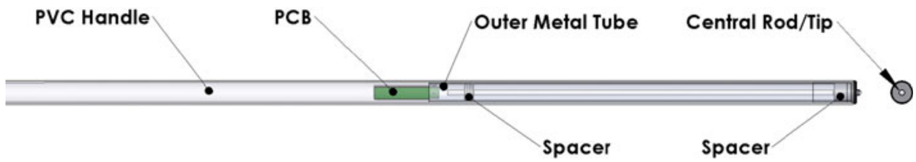

Fig. 1 Cross section of the Grassmaster II probe, showing the main components (were PCB is the proprietary circuit board)

The Grassmaster II includes an upper user interface with a LCD and a small keyboard which also houses the electronic circuit. Inside is a small proprietary circuit board (PCB, Fig. 1) which sends out a 5 V oscillation signal to the ground. The lower part of the instrument is made of a plastic tube of approximately 1.20 m length. Inside is an outer metal tube which runs from about half way up the probe length, back to the ground level, insulated by the plastic outer tube. Held in the centre of this tube, with insulated collars, is a solid stainless rod that runs the same half-probe length and ends up in contact with the ground. This rod transmits the 5 V oscillation signals to the external dielectric material, which in this case is the grass.

The probe produces an electric field that is modified by the pasture close to it. The modified field is detected as a change in capacitance by the electronic circuit within the probe. This capacitance change is proportional to the water content of the grass. Because the dry matter content is highly correlated with the water content, the probe capacitance change is calibrated to the pasture yield, with linear calibration equations used to correlate readings taken on pasture over a short seasonal time, with measured dry matter production.

The logical integrated circuit in the Grassmaster probe produces waveforms using an oscillator. The microprocessor counts the time necessary for 128 waveforms from the oscillator to be completed, and this time is then presented by the manufacturer as the Meter Reading. The higher the grass density around the probe, the higher will be the time count and thus the Meter Reading. The Corrected Meter Reading, CMR is then obtained by subtracting from this reading the air reading obtained at the start of the paddock. The theory and operation of the capacitance meter is further explained by Vickery and Nicol (1982).

The Grassmaster II is sensitive to pasture sward type and changes in the grass structure (Virkajarvi 1999) with the season affecting the correlation of dry matter with water content. For example, when the pasture goes to seed, or the amount of dead matter changes, the relationship with dry matter density and water content change. The objective of the calibration technique is to account for these predictable variations, and therefore improve the accuracy of the pasture measurement system in determining pasture yield.

The probe uses an electronic data registration circuit that allows for organization of the readings per parcel and the transfer of data to a desktop computer for later treatment. When calibrated, the operator keys the parameters of the linear regression equation (slope and intercept), which allows for a direct and automatic reading of the quantity of estimated dry matter (DM_{est}) per unit area (kg DM ha^{-1}). The Grassmaster II manufacturer presents two calibration equations (Eqs. 1 and 2) to estimate the pasture dry matter yield based in the CMR measurement. These equations were calculated for New Zealand dairy pasture of 80/20 rye-clover mix with dry matter content of 14–16% and for residual dairy pasture measurements, considered also as an effective "base line" equation, respectively.

$$DM_{est1} = 0.72CMR\text{-}2200 \tag{1}$$

$$DM_{est2} = 0.48CMR\text{-}300 \tag{2}$$

were DM_{est} is the pasture dry matter yield (kg ha^{-1}) and the CMR is the Corrected Meter Reading.

Pasture dry matter yield measurement

Measuring pasture dry matter yield (DM_{meas}) was carried out using the following standard procedure:

- In areas subject to animal grazing, 1 m^2 enclosure cages were installed at the beginning of the vegetative cycle of the crop (September), in different geo-referenced locations of the parcel; the 1 m^2 metal rim was used in areas that were not subject to grazing;
- Manual cutting (to 20–30 mm above ground level) of the pasture as required; about 2–4 cuttings (between January and May), depending on the agricultural year with regard to temperature and precipitation; the samples were stored in marked plastic bags;
- These samples were weighed, in the laboratory, to determine the green matter production per hectare (GM). Sub-samples in small paper bags were placed in a 65°C oven for 72 h to determine the moisture content. The moisture content value was then used to calculate pasture dry matter yield (DM).

Experimental procedure

The experiment in this study was carried out in three phases (Fig. 2): evaluation (in 2007), calibration (in 2007) and validation (in 2008 and 2009).

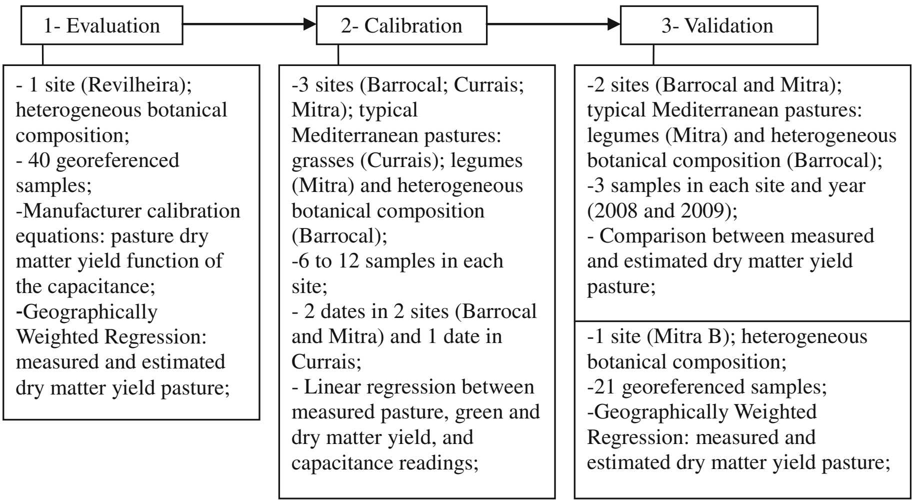

Fig. 2 Sequence of implemented experimental procedure

Evaluation phase

The evaluation phase was carried out in March 2007, in the Revilheira farm (co-ordinates 38°27.9′N and 7°25.7′W), a 6 ha heterogeneous botanical composition pasture (grasses, mainly *Dactilis glomerato,* legumes, mainly *Trifolium subterraneum*, and others species), in a pre-flowering phenological stage. The Grassmaster probe was used to measure the capacitance in 40 enclosure cages, geo-referenced using a Trimble 4700, RTK survey grade receiver. Each measurement was preceded by an air humidity level correction, before any data were collected by the probe. The capacitance readings were registered after the instrument had been positioned vertically over the vegetation (Fig. 3), with a 200–300 mm separation from the operator's body. In each 1 m^2 sample, 30 readings were carried out with the probe.

Following the readings, the pasture inside each exclusion box was cut to 20–30 mm above ground level and the measured pasture dry matter yield was determined according to the conventional method mentioned above. With regard to data treatment, the measured dry matter yield and the capacitance determined by the probe were used in an Excel spreadsheet to carry out linear regression between these parameters. Also the measured and the estimated dry matter yield based on the calibration equations suggested by the manufacturer were compared.

Calibration phase

The calibration phase was carried out between March and May 2007, on three dairy farms (Currais, Mitra and Barrocal), which represent typical pastures in the Alentejo region: (a) grasses; (b) legumes; (c) heterogeneous botanical composition, respectively. The plant species prevalent in each of the sites for testing were:

- Mitra (co-ordinates 38°32.2′N and 8°01.1′W): exclusively legumes pasture (*Trifolium subterraneum*), subject to grazing by cattle;
- Currais (co-ordinates 38°30.1′N and 7°48.6′W): exclusively grass pasture (*Lolium multiflorum* Lam); this type of pasture was not subject to grazing, and was cut for hay and forage;
- Barrocal (co-ordinates 38°30.4′N and 8°02.4′W): heterogeneous pasture of grasses and legumes (*Trifolium glanduriferu*, *Ornithopus sativus*, *Trifolium incarnatum*, *Trifolium vesiculosum*, *Trifolium subterraneum*, *Lolium multiflorum* and *Dactilis glomerato*), subject to grazing by sheep.

Fig. 3 Electronic capacitance probe Grassmaster II in experimental field tests

In Currais, the field tests were conducted only in March 2007 (in pre-flowering phenological stage), because this field was integrated in a crop rotation scheme and the farmer had cut the forage in April and had cultivated the soil for planting a spring-summer crop. In Barrocal, the field tests were carried out on two dates (March and April 2007), at the same phenological stage (pre-flowering). In Mitra, the field tests were carried out on two dates (March and May 2007), at different phenological stages, pre-flowering and flowering, respectively.

The 1 m^2 metal rim was used to isolate the pasture area of each sample in the calibration processes carried out in these three locations. In each field, six randomly distributed pasture samples were collected. For each sample, thirty readings were carried out with the Grassmaster and averaged. Then the pasture within the metal rim was cut to 20–30 mm above ground level and the actual pasture dry matter yield was measured using the traditional method, mentioned above.

The capacitance meter was calibrated, using a spreadsheet to establish the linear regression equations between the weight of the herbage, green and dry matter (direct measurements) and the capacitance meter reading (indirect measurements). This technique requires a relatively small amount of labour. Usually two people are needed, one to operate the capacitance probe and the other to cut the pasture. In this way, six vegetation samples for developing a calibration equation can be collected in approximately 0.5 h.

Validation phase

The validation phase was carried out in April and May 2008 and April 2009, on three dairy farms: Barrocal, Mitra and Mitra B. In Barrocal and Mitra sites, the validation was carried out 1 and 2 years after the second period of calibration, with the above mentioned procedure having been used in the calibration phase, except with regard to the number of samples. In this case, only three randomly distributed samples were collected from each locality in each year. With regard to data treatment, the measured and the estimated dry matter yield, estimated by the probe based on the equation established in the calibration phase for each location, were compared. In Mitra B (co-ordinates 38°31.9′N and 8°00.4′W), a 14 ha heterogeneous pasture area, the capacitance probe, programmed with the calibration equation obtained in 2007 in Barrocal (heterogeneous botanical composition) and validated in 2008, was used to estimate the pasture dry matter yield in 21 enclosure cages on the pasture, geo-referenced using a Trimble 4700 RTK survey grade receiver. In each 1 m^2 sample, thirty readings were carried out with the probe and the mean value of pasture dry matter yield, obtained automatically by the probe and shown on the monitor was registered. Then the pasture within each enclosure cage was cut and the actual pasture dry matter yield was determined using the conventional method, mentioned above.

With regard to data treatment, the measured dry matter yield and the capacitance determined by the probe were used in a spreadsheet to establish the linear regression between these parameters. Also, the measured and the estimated dry matter yield were compared, as determined by the probe based on the established equation from experiments carried out in a parcel of pasture with similar characteristics (Barrocal—heterogeneous botanical composition).

Statistical treatment

In the different phases of this research (evaluation, calibration and validation) correlations were established, respectively: (1) between the measured dry matter and the capacitance registered by the probe (evaluation phase); (2) between the measured green matter and the capacitance and between the dry matter and the capacitance (calibration phase); (3) between the measured dry matter and the dry matter estimated by the probe, previously programmed (evaluation and validation phases).

The statistical treatment of the results with regard to calibration of the capacitance probe consisted in analysing the regression with a 5% probability level (statistical $P < 0.05$ significance level, basis of all declared significant differences between comparisons of means), using a spreadsheet of the Excel program.

After obtaining pasture properties, a set of map layers in raster format, with a 5 m resolution, was generated. All maps were produced with the ArcMap/Spatial Analyst module of the ArcGIS (version 9.3.1, ESRI Inc, Redlands, CA, USA), considering an ordinary kriging interpolator, with a spherical semi-variogram and a variable search radius (five neighbours with a minimum of two neighbours).

Results and discussion

Table 1 shows the mean ± standard deviation of CMR, measured and estimated pasture dry matter yield in kg ha^{-1}, and the corresponding root mean square error (RMSE) using the manufacturer's calibration equations (1 and 2). Figure 4 shows the poor correlation ($R^2 = 0.20$; $P < 0.01$) between the measured pasture dry matter yield (DM_{meas}) and the capacitance (CMR) at Revilheira site. These results are based on the calibration equations proposed by the manufacturer (Eqs. 1 and 2).

Figure 5 presents the maps of the geo-referenced information of the measured pasture dry matter yield at Revilheira site and the estimated pasture dry matter yield for the same site based on the two equations proposed by the manufacturer. The great variability of pasture at the Revilheira site (dry matter content of 12–44%; dry matter yield of 1 398 ± 605 kg ha^{-1}, range between 613 and 3 341 kg ha^{-1}), might justify this poor correlation. Another contributing factor might be related to the fact that Eq. 1 was developed in paddocks with a good cover and an average minimum production of 2 500 kg ha^{-1}. On the other hand, Eq. 2 was calibrated for low or residual paddocks, with high dead material content, which was not the case of the pasture at the Revilheira site.

The results of the evaluation tests carried out at Revilheira site justify the need for calibration of the probe as a function of pasture characteristics, which is referred to by the manufacturer as well as by other authors (Hirata 2000; Sanderson et al. 2001).

Table 2 shows the pasture characterization at three sites used for the establishment of the calibration equations. The coefficients of variation in calibration tests ranged between 15 and 19%. These values were similar to those (CV = 21%) presented by Donovan et al. (2002) and the 13.3 and 15.4% reported by Stockdale and Kelly (1984) to estimate the

Table 1 Mean ± standard deviation of CMR, measured and estimated pasture dry matter yield, and the corresponding RMSE using the manufacturer's calibration equations (1 and 2)

Site	CMR	DM_{meas} (kg ha^{-1})	DM_{est1} (kg ha^{-1})	$RMSE_{est1}$ (kg ha^{-1})	DM_{est2} (kg ha^{-1})	$RMSE_{est2}$ (kg ha^{-1})
Revilheira	4 851 ± 785	1 398 ± 605	1 293 ± 565	620	2 029 ± 377	835

CMR capacitance, DM_{meas} dry matter measured, DM_{est1} and DM_{est2} dry matter estimated using the calibrated manufacturer equations, *RMSE* root mean square errors

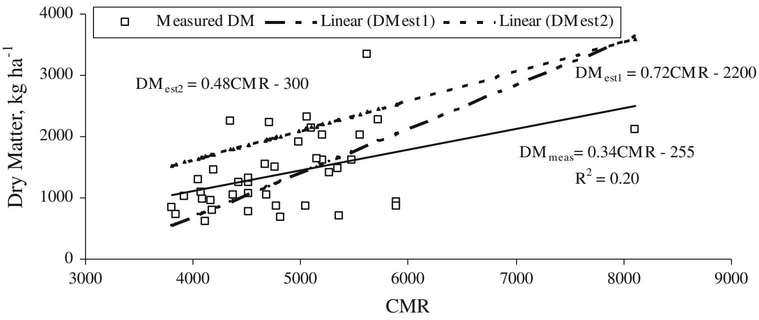

Fig. 4 Linear regression equation between capacitance (CMR) and dry matter measured (DM_{meas}) in Revilheira site; plotted against the values of dry matter estimated by manufacturer's calibration equations (DM_{est1} and DM_{est2})

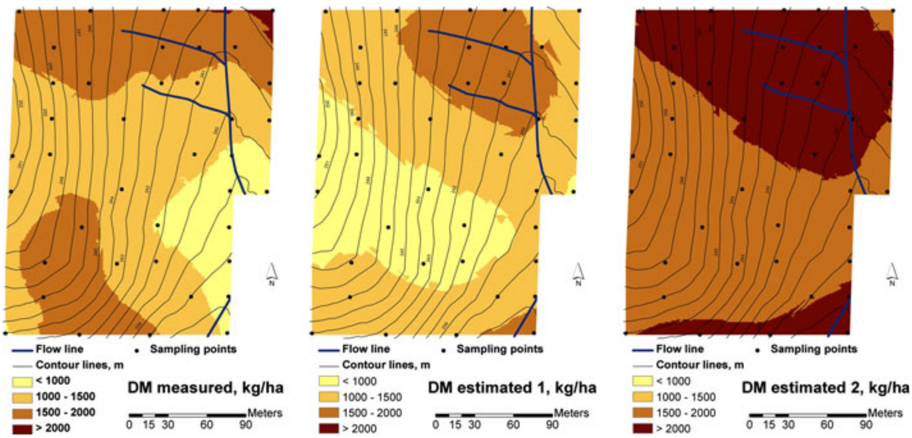

Fig. 5 Maps of pasture dry matter yield in Revilheira site (area of 6 ha): measured (*left*) and estimated (*centre* and *right*) based on the manufacturer's equations (*centre*: $DM_{est1} = 0.72CMR\text{-}2200$; and *right*: $DM_{est2} = 0.48CMR\text{-}300$)

Table 2 Pasture characterization at three sites used to establish the calibration equations

Site	n	CV (%)	DM (%)	DM (kg ha^{-1})	CMR	DM_{meas} (kg ha^{-1})	GM_{meas} (kg ha^{-1})
Mitra	12	19	[11–18]	[1 278–3 663]	7 621 ± 1 132	2 222 ± 771	16 218 ± 6 392
Currais	6	18	[21–28]	[711–2 151]	6 771 ± 1 436	1 499 ± 555	6 187 ± 2 822
Barrocal	12	16	[15–23]	[552–2 167]	6 400 ± 1 297	1 344 ± 578	7 352 ± 3 121

n number of samples, *CV* variation coefficient, *DM* dry matter, *CMR* capacitance, DM_{meas} dry matter measured, GM_{meas} green matter measured

herbage mass with the single-probe electronic capacitance meter, respectively before and immediately after grazing. Figure 6 shows the general aspect of the pasture species used to establish the calibration equations.

The actual capacitance (CMR) readings by the Grassmaster II probe and the measured pasture green matter (GM) and dry matter (DM) yield, in kg ha^{-1} were used to establish

Fig. 6 General aspect of the calibration sites with pastures typical of the Mediterranean conditions

calibration equations adapted to local Mediterranean conditions at three sites (Fig. 7). At all sites, higher correlation coefficients were observed with GM than with DM, which was expected, given the physical principles behind the capacitance probe; essentially this device responds to the wet biomass (Hanna et al. 1999) and, according to the manufacturer of the probe, water is, by far, the material that affects the probe signal the most. Nevertheless, for the farmer the primary interest is reliable estimation of nutritional feed availability for the grazing animal and the estimation of energy value of animal feed is based on DM (Hanna et al. 1999). For this reason, only the calibration of DM will be considered in this work.

High overall regression coefficients were obtained between the capacitance and the DM in grasses (Currais site; $R^2 = 0.90$; $P < 0.01$) and heterogeneous botanical mixture (Barrocal; $R^2 = 0.87$; $P < 0.001$). These confirm the high correlation coefficients ($R^2 = 0.88$–0.98) reported by Hirata (2000) and Ogura and Hirata (2001) for estimating dry matter production of "Bahia grass" (*Paspalum notatum*) pasture grazed by cattle, in two seasons, based on capacitance measurements. These authors concluded that the electronic capacitance probe is useful for monitoring the spatial pattern of the herbage mass, herbage production and consumption, and for relating consumption to the ingestive behaviour of grazing animals.

At the Mitra site (legumes species), a moderate regression coefficient ($R^2 = 0.48$; $P < 0.05$) was obtained. For the experiments carried out at Barrocal and Mitra site, on two dates (March and April, and March and May, respectively), the best correlation was obtained when using data from both dates. This improvement of the correlation coefficients was more important in Barrocal site due to the fact that the crops were at the same phenological stage (pre-flowering). The possible reasons for moderate regression coefficients between the capacitance and the DM at Mitra site include uneven ground (e.g., dips and holes) in pastures, trampling or lodging of vegetation, the selection of sampling points and, most notably, that the two dates correspond to different phenological stages (respectively pre-flowering and flowering). The poor correlation on clover also can be explained by the fact that the probe measures cross-sectional area interface of the radio frequency by the actively growing grass (moisture and perhaps some mineral content in the plant affecting readings), and that the probe has a very limited "volume or three dimensional measurement capability". Clover on the other hand can be viewed, effectively, as a stem with an umbrella, offering a far less "cross-sectional area disturbance" situation of the radio field emanating from the probe.

Table 2 shows that the pasture at Mitra site was clearly the most productive (mean GM_{meas} superior to 16 000 kg ha^{-1}) with the lowest percentage of DM, which might have also contributed to the lower correlation of the data.

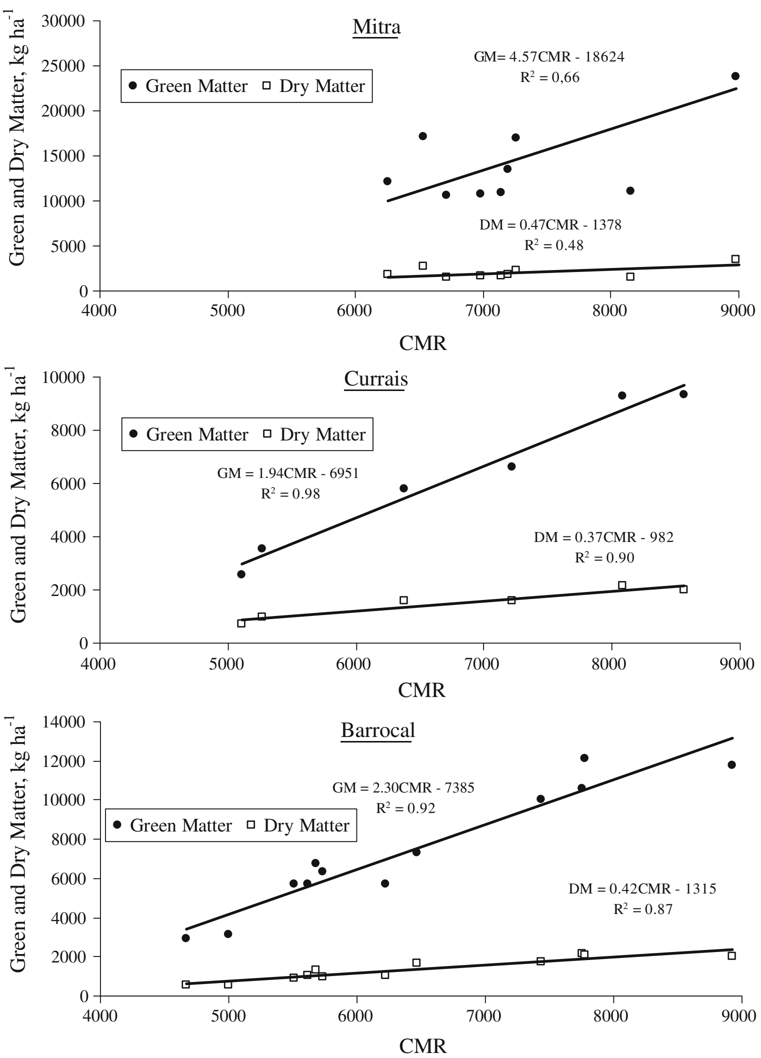

Fig. 7 Calibration equations between the capacitance (CMR) readings and measured green (GM) and dry matter yield (DM) in three sites

In 2008 and 2009, the regression equations obtained in the experiments carried out in 2007 were validated at two sites (Barrocal and Mitra) and the results show a difference of less than or equal to 20%, between the measured mass and the estimated mass (Fig. 8). The pasture estimation RMSE was 456 kg ha^{-1} at the Mitra site and 130 kg ha^{-1} at the Barrocal site, results that reflect the lower confidence level of the calibration equation (see Fig. 7) obtained in legumes species (Mitra site) in comparison with the calibration equation established for the heterogeneous botanical mixture (Barrocal site).

Later on in 2008, the equation obtained for the Barrocal site (heterogeneous botanical composition: $DM_{est} = 0.42CMR\text{-}1315$) was used to estimate the dry matter yield of pasture at Mitra B site (heterogeneous botanical composition; dry matter yield of

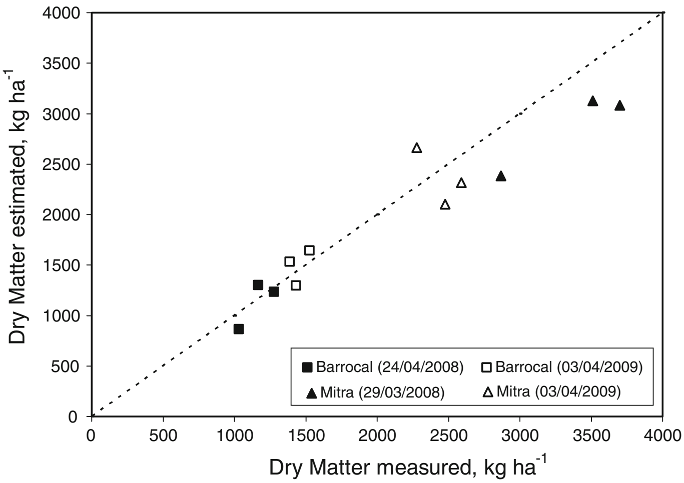

Fig. 8 Validation of the predictions of dry matter yield (kg ha^{-1}) in two locations and 2 years

Table 3 Mean ± standard deviation of CMR, measured and estimated pasture dry matter yield, and the corresponding RMSE using the calibration equation obtained in Barrocal site

Site	CMR	DM_{meas} (kg ha^{-1})	DM_{est} (kg ha^{-1})	RMSE (kg ha^{-1})
Mitra B	5 696 ± 2 029	2 062 ± 960	1 681 ± 743	545

CMR capacitance, DM_{meas} dry matter measured, DM_{est} dry matter estimated, *RMSE* root mean square error

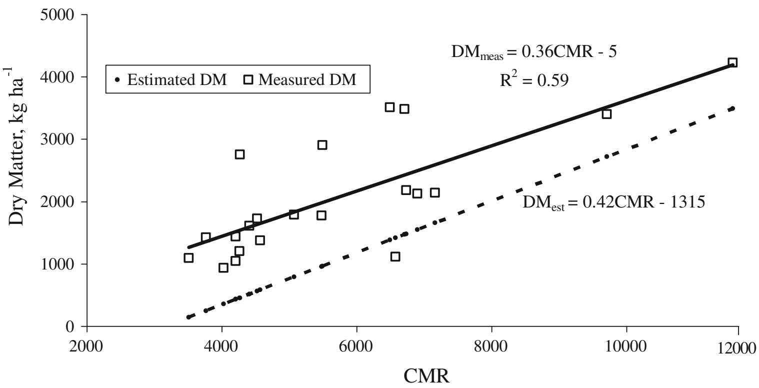

Fig. 9 Linear regression equation between capacitance (CMR) and dry matter measured (DM_{meas}) in MitraB site; plotted against the values of dry matter estimated by Barrocal calibration equation (DM_{est})

2 062 ± 960 kg ha^{-1}; range between 939 and 4 226 kg ha^{-1}; dry matter content of 24–46%). The capacitance of the 21 geo-referenced samples (Table 3) present a moderate regression coefficient ($R^2 = 0.59$; $P < 0.001$) with the measured pasture dry matter yield (Fig. 9), despite the great variability of the DM percentage of this plot. Figure 10 presents the maps of the geo-referenced information of the measured and the estimated pasture dry matter yield at the Mitra B site. The smaller regression coefficients observed in the

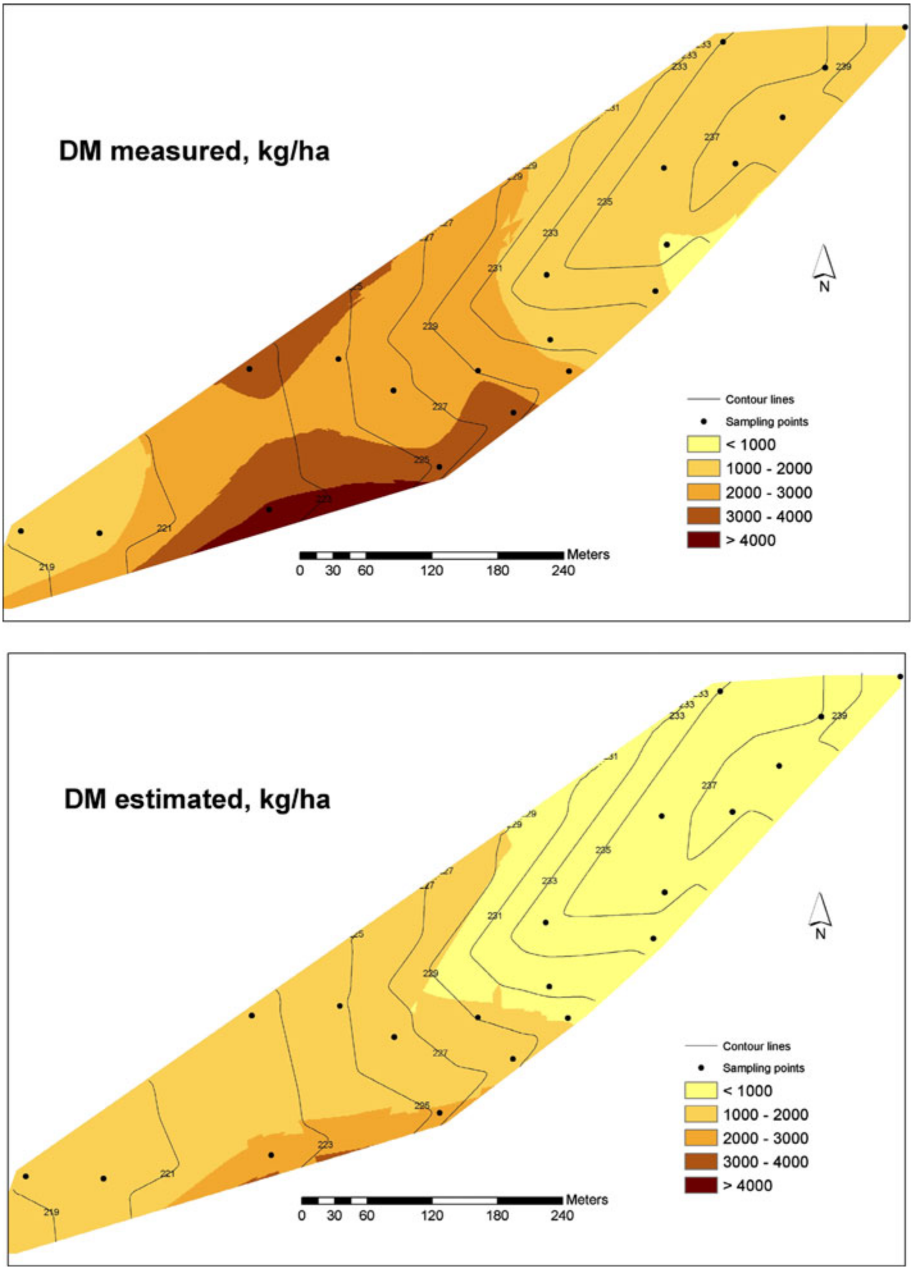

Fig. 10 Maps of measured (*above*) and estimated (*bottom*) pasture dry matter yield in Mitra B site (area of 14 ha) based on the Barrocal equation ($DM_{est.} = 0.4155CMR\text{-}1315.4$)

validation carried out at Mitra B, comparatively to the validations carried out in 2008 and 2009 in the pastures of Mitra and Barrocal, shows that despite it also being a mixture of species, as was the case of the Barrocal pasture which served as basis for the calibration equation, it will be necessary to carry out a study of the different mixtures of botanical species that are more widely used in the region.

Due to the degree of uncertainty associated with calibration and validation of this capacitance probe, specially in legumes species (Mitra site), its general application should be approached with some reservation, with regard to estimation of pasture dry matter yield in Mediterranean conditions; a fact quoted by other authors. Cauduro et al. (2006) obtained poor regression coefficients ($R^2 = 0.149$) and have acknowledged susceptible error factors, such as the existence of a high quantity of dead vegetation in the form of hay at the soil surface. Murphy et al. (1995) and Virkajarvi (1999) reported moderate mean regression coefficients ($R^2 = 0.42$ and $R^2 = 0.44$, respectively). Currie et al. (1987) have registered a moderate overall regression coefficient ($R^2 = 0.50$) with the linear calibration equation being statistically significant between the probe readings and green and dry weight of forage for all regressions. The proportion of variance (R^2) accounted for by the model presented by Donovan et al. (2002) was 72%.

The results obtained in this work demonstrate the need for calibration of the probe not only in relation to the different botanical species found in the Mediterranean flora, but also, within each species, to the different vegetative development stages. This characteristic has already been reported by other research teams, such as Virkajarvi (1999), Sanderson et al. (2001) and Zanine et al. (2006). Also the Grassmaster manufacturer, although providing reference equations for estimating pasture mass (Eqs. 1 and 2), emphasizes the need for adjusting the calibration equations according to the characteristics of the pasture. Thus, it is important that in future capacity probe calibrations, the botanical issues be studied in more detail, in order to clarify whether the specific characteristics of the legumes morphology, usually with higher water content than the grasses or other species, and with a creeping growth habit, require a different procedure for the readings with the capacitance probe. According to Hanna et al. (1999), seasonal adjustments to calibration equations were found to be necessary as the moisture content of pasture vegetation varies with season and live/dead material ratio.

The fact that the validation of regression equations in 2008 and 2009 shows a difference of less than or equal to 20%, between the measured and the estimated dry matter per hectare (Fig. 8) is very positive and, in practice, these deviations from the regression line are not an obstacle for the pastureland managers to quantify the dry matter available for animal grazing and for application of precision management techniques.

It is foreseen that the data obtained in this work, together with other data obtained by the Grassmaster II manufacturer be used to review the existing equations and produce more robust and consistent ones. On the other hand, the manufacturer is presently working on developing another instrument to quickly advise the percentage of DM of material on the day in question (day of readings) and to input that data to the LCD interface. Measuring the soil itself (with a cropped grass cover) might also be very informative, and replace the "air" readings. For Hanna et al. (1999), future devices should be insensitive to plant moisture, thus permitting the remote dry weighing of pasture.

Conclusions

Regression equations were used to relate the directly measured dry matter mass with the indirect estimates obtained using a Grassmaster II capacitance probe. In two of the three locations of the experiment in typical Mediterranean pastures, the regression coefficients were high ($R^2 = 0.90$, $P < 0.01$ in grasses; and $R^2 = 0.87$, $P < 0.001$ in heterogeneous botanical mixture). In legumes, the regression coefficient was moderate ($R^2 = 0.48$; $P < 0.05$).

In 2008 and 2009, the prediction equations were validated in two of the locations, with a deviation equal to or less than 20% between the estimated and the measured pasture dry matter yield and RSME values of 130 kg ha^{-1} in heterogeneous botanical composition and 456 kg ha^{-1} in legumes. Also, one of the calibration equations at real scale was validated, with geo-referenced samples, leading to a moderate correlation ($R^2 = 0.59$; $P < 0.001$) in a heterogeneous botanical mixture. The results indicate that the capacitance probe together with a GPS receiver might support site-specific management of pastures which would be useful in large areas.

These results also reinforce the recommendations of other works and of the Grassmaster manufacturer in regards to the need for adjustment of the calibration equations in function of pasture characteristics (species, live/dead material ratio) and of seasonal changes of the moisture content of pasture vegetation.

This work is the starting point for a broader study, involving the manufacturer of the Grassmaster probe, which will aim at covering a wider range of botanical species, in order to test the applicability of the probe for estimating dry matter yield in pastures with mixed species which are typical of the great biodiversity that characterize the Mediterranean flora.

Acknowledgments This project was sponsored by the AGRO Programme of the Ministry of Agriculture of Portugal. The authors would like to thank the availability and contribution of Novel Ways Electronic, manufacturer of the Grassmaster II probe, to the discussion of the results.

References

Agouridis, C., Stombaugh, T., Workman, S., Koostra, B., Edwards, D., & Vanzan, E. (2004). Suitability of a GPS collar for grazing studies. *Transactions of the ASAE, 47*, 1321–1329.

Aiken, G. E., & Bransby, D. I. (1992). Observer variability for disk meter measurements of forage mass. *Agronomy Journal, 84*, 603–605.

Bailey, J. S., Wang, K., Jordan, C., & Higgins, A. (2001). Use of precision agriculture technology to investigate spatial variability in nitrogen yields in cut grassland. *Chemosphere, 42*, 131–140.

Barbari, M., Conti, L., Koostra, B., Masi, G., Sorbetti Guerri, F., & Workman, S. (2006). The use of global positioning and geographical information systems in the management of extensive cattle grazing. *Biosystems Engineering, 95*, 271–280.

Cauduro, G. F., Carvalho, P., Barbosa, C., Lunardi, R., Pilau, A., Freitas, F., & Silva, J. (2006). Comparação de métodos de medida indirecta de massa de forragem em pasto de azevém anual (*Lolium Multiflorum Lam.*). (Comparision of indirect methods for measuring forage mass under annual ryegrass ((*Lolium Multiflorum Lam.*)). *Ciência Rural*, *36*, 1617–1623 (in Portuguese).

Currie, P. O., Hilken, T. O., & White, R. S. (1987). Evaluation of a single probe capacitance meter for estimating herbage yield. *Journal of Range Management, 40*, 537–541.

Donovan, M., Dillon, P., Rath, M., & Stakelum, G. (2002). A comparison of four methods of pasture mass estimation. *Irish Journal of Agricultural and Food Research, 41*, 17–29.

Franca, A., Roggero, P., Porqueddu, C., & Caredda, S. (2003). The use of the Grassmaster as a simplified method to estimate dry matter yield on annual self-reseeding medics and clovers. *Italian Journal of Agronomy, 7*, 103–110.

Ganguli, A., Vermeire, L., Mitchell, R., & Wallace, M. (2000). Comparison of four nondestructive techniques for estimating standing crop in shortgrass plains. *Agronomy Journal, 92*, 1211–1215.

Hanna, M., Steyn-Ross, D., & Steyn-Ross, M. (1999). Estimating biomass for New Zealand pasture using optical remote sensing techniques. *Geocarto International, 14*, 89–94.

Hirata, M. (2000). Quantifying spatial heterogeneity in herbage mass and consumption in pastures. *Journal of Range Management, 53*, 315–321.

Hutchings, N. (1991). Spatial heterogeneity and other sources of variance in sward height as measured by the sonic and HFRO sward stick. *Grass Forage Science, 46*, 277–282.

Karl, M. G., & Nicholson, R. A. (1987). Evaluation of the forage disk method in mixed grass rangeland in Kansas. *Journal of Range Management, 40*, 467–471.

King, J., Dampney, P., Lark, R., Wheeler, H., Bradley, R., & Mayr, T. (2005). Mapping potential crop management zones within fields: Use of yield-map series and patterns of soil physical properties identified by electromagnetic induction sensing. *Precision Agriculture, 6*, 167–181.

Murphy, W. M., Silman, J. P., & Mena Barreto, A. D. (1995). A comparison of quadrat, capacitance meter, HFRO sward stick, and rising plate meter for estimating herbage mass in a smooth-stalked meadowgrass-dominant white clover sward. *Grass Forage Science, 50*, 452–455.

Ogura, S., & Hirata, M. (2001). Two-dimensional monitoring of spatial distribution of herbage mass in a bahia grass (*Paspalum notatum Flugge*) pasture grazed with cattle. *Grassland Science, 47*, 453–459.

Reese, G., Bayn, R., & West, N. (1980). Evaluation of double-sampling estimators of subalpine herbage production. *Journal of Range Management, 33*, 300–306.

Rook, A. J., Dumont, B., Isselstein, J., Osoro, K., Wallis, D., Parente, G., et al. (2004). Matching type of livestock to desired biodiversity outcomes in pastures—a review. *Biology Conservation, 119*, 137–150.

Sanderson, M. A., Rotz, C. A., Fultz, S. W., & Rayburn, E. B. (2001). Estimating forage ass with a commercial capacitance meter, rising plate meter, and pasture ruler. *Agronomy Journal, 93*, 1281–1286.

Schellberg, J., Hill, M. J., Gerhards, R., Rothmund, M., & Braun, M. (2008). Precision agriculture on grassland: Applications, perspectives and constraints. *European Journal of Agronomy, 29*, 59–71. doi:10.1016/j.eja.2008.05.005.

Sharrow, S. (1984). A simple disc meter for measurement of pasture height and forage bulk. *Journal of Range Management, 37*, 94–95.

Silva, S. C., & Cunha, W. F. (2003). Métodos indiretos para estimar a massa de forragem em pastos de *Cynodon* spp. (Indirect methods for estimating herbage mass in *Cynodon* spp. swards). *Pesquisa Agropecuária Brasileira, 38*, 981–989 (in Portuguese).

Stockdale, C., & Kelly, K. (1984). A comparison of a rising-plate meter and an electronic capacitance meter for estimating the yield of pastures grazed by dairy cows. *Grass and Forage Science, 39*, 391–394.

Turner, L., Udal, M., Larson, B., & Shearer, S. (2000). Monitoring cattle behavior and pasture use with GPS and GIS. *Canadian Journal of Animal Science, 80*, 405–413.

Vickery, P. J., & Nicol, G. R. (1982). *An improved electronic capacitance meter for estimating pasture yield: Construction details and performance tests* (pp. 1–22). Australian Animal Research Laboratories technical paper no. 9. Armidale: CSIRO.

Virkajarvi, P. (1999). Comparison of three indirect methods for prediction of herbage mass on timothy-meadow fescue pastures. *Soil and Plant Science, 49*, 75–81.

Zanine, A. M., Santos, E. M., & Ferreira (2006). Principales métodos de evaluación de pasturas (Main methodologies for evaluation of pastures). *Revista Electrónica de Veterinaria REDVET*, *España, VII*(11), 1–13 (in Spanish).