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NON-DESTRUCTIVE MEASUREMENTS OF BIOMASS IN MILLET, COWPEA, GROUNDNUT, WEEDS AND GRASS SWARDS USING REFLECTANCE, AND THEIR APPLICATION FOR GROWTH ANALYSIS

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SUMMARY

A simple hand-held reflectometer was used to estimate the shoot dry matter of pearl millet (*Pennisetum glaucum*), groundnut (*Arachis hypogaea*), cowpea (*Vigna unguiculata*), weeds and grass swards non-destructively. While the instrument was able to predict shoot dry matter well for single, standing millet and cowpea plants and proved useful for a growth analysis of millet, its reliability was unsatisfactory for groundnut. For millet, the slope of two separate regressions between the difference of reflectance ratios and shoot dry matter, taken 10 days apart, was almost identical. This suggests a possible simplification in future crop growth models. The usefulness of the instrument for estimating dry matter in natural species mixtures such as weeds and grasses depended on the homogeneity of the mixture and the uniformity of their physiological state.

Medición de la biomasa utilizando la reflexión

RESUMEN

Se utilizó un sencillo reflectómetro de mano para estimar, sin destruir, la materia seca de los brotes del mijo perlado (*Pennisetum glaucum*), el cacahuete (*Arachis hypogaea*), el caupí (*Vigna unguiculata*), las malas hierbas y los céspedes de hierba. Aunque el instrumento pudo predecir la materia seca de los brotes para el mijo ceburro y las plantas de caupí, y demostró ser útil para el análisis del crecimiento del mijo, su fiabilidad fue insatisfactoria para el cacahuete. Para el mijo, la curva de dos análisis de regresiones diferentes entre la diferencia de los índices de reflexión y la materia seca de los brotes, tomados con 10 días de diferencia, era casi idéntica. Esto sugiere una posible simplificación de los modelos futuros de crecimiento de cultivos. La utilidad de este instrumento para estimar la materia seca en mezclas de especies naturales como las malas hierbas y la hierba depende de la homogeneidad de la mezcla y uniformidad de su estado fisiológico.

INTRODUCTION

The estimation of standing crop biomass using reflectance measurements has become a widespread practice in recent years. It is based on the principle that incoming radiances at wavelengths between 620 and 680 nm (red) are strongly

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absorbed by chlorophyll in photosynthetically active tissues while those at wavelengths between 790 and 900 nm (near-infrared) are scattered as a result of refractive index differences between intercellular air spaces and hydrated cells (Colwell, 1974; Tucker, 1979; Tucker and Sellers, 1986). Today advances in the use of remote sensing techniques from aircraft or satellites even allow forest inventories in temperate areas (Zhu and Evans, 1992) and the determination of the composition of vegetation types in sub-tropical countries (Frederiksen and Lawesson, 1992). On a smaller scale, different instruments measuring radiation interception and reflectance have been used to estimate leaf area index (Asrar *et al.*, 1984), crop residue coverage in wheat (Aase and Tanaka, 1991) and the shoot biomass of homogeneous standing crops such as groundnut (Nageswara *et al.*, 1992), maize and soyabean (Tucker *et al.*, 1979), alfalfa pastures (Mitchel *et al.*, 1990) and grasses (Mayhew *et al.*, 1984). However, little information is available about the usefulness of reflection measurements in the Sahel to estimate the shoot dry matter of a crop like millet with a rapidly increasing leaf area index, and of variable mixtures of species such as weeds and grass swards. If such non-destructive techniques could be used successfully, the determination of growth rates would be quicker and cheaper and experimental plots could become smaller. Also the monitoring of weeds and patchy grasslands, which provide fodder for animals in the savanna areas of the semi-arid tropics, would be much easier. We therefore measured reflectances in millet, groundnut, cowpea, weeds and grasses with a simple two-band reflectometer and compared the results with those from destructive harvests of above-ground biomass.

MATERIALS AND METHODS

Differential reflectometer

The design of the instrument used in our experiments was similar to the one reported by Nageswara *et al.* (1992). It consisted of a plastic collimator tube 150 mm long, with an inside diameter of 50 mm, suspended vertically from the apex of a pyramidal frame made from a 4 mm diameter steel rod. The top of the tube was closed and the inside painted matt black. Two light-sensitive diodes were fixed centrally 50 mm from the mouth inside the tube. The mouth of the tube was 0.70 m above the ground, so that the sensors covered a circle of soil and plants approximately 0.75 m in diameter. For millet at 40 days after planting (DAP) the mouth was raised to a height of 1.25 m above the ground, with the sensors covering a circle of 1.30 m diameter.

One of the diodes (ER-300) was maximally sensitive to red light (R) of wavelength 660 nm and the other (XC880A) to light in the near-infrared (NIR) of wavelength 880 nm. Power outputs from the two diodes when maximally illuminated were 100 and 10 μA, respectively.

The outputs from both diodes were processed using three sections of a quad operational amplifier type OP400GP (Fig. 1). The first stage consisted of a current–to–voltage converter followed, in the case of the NIR diode, by further

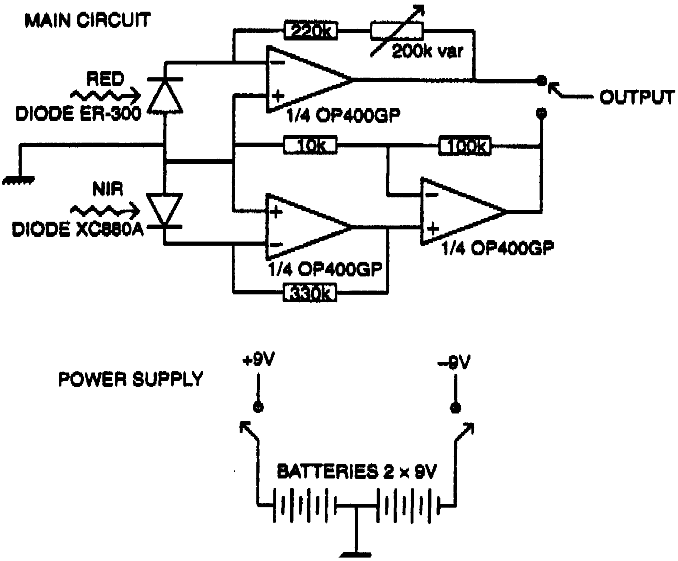

Fig. 1. Circuit diagram of the differential reflectometer used to measure radiation interception of crops.

amplification by a factor of 11 to allow for the different power outputs of the two diodes. The output of the R diode amplifier could be adjusted by means of the 200 kΩ variable resistor. In bright sunlight, outputs ranged from 1 to 3 volts and were measured and displayed using a 3½ digit digital voltmeter. The unit was powered using two 9 V PP9 batteries connected with each other as shown in Fig. 1. All the electronic components were housed in a clear plastic box 17 × 11 × 8 cm mounted next to the collimator tube on the metal frame. The whole apparatus, including the frame, weighed less than 2 kg.

The instrument was set up before and at regular intervals during a measurement period by placing it over a 1 m square sheet of matt white paper and adjusting the variable resistor until the output from the R diode was the same as that from the NIR diode. All measurements were taken in bright sunlight between 1000 and 1530 local time. Under these conditions the ratio of the readings from the two sensors over white paper remained constant even though the actual numerical values could have changed with the elevation of the sun or the amount of dust in the atmosphere. To avoid distortions due to changing light intensity or differences in soil surface colour, reflectances from samples were expressed as the normalized difference vegetation index, NDVI (Tucker and Sellers, 1986):

$$\mathrm{NDVI} = (\mathrm{NIR} - \mathrm{R})/(\mathrm{NIR} + \mathrm{R})$$

where NIR is the amplified signal from the near-infrared sensor and R the amplified signal from the red sensor.

Crops

All data were collected in 1993 at the ICRISAT Sahelian Center, Sadoré, Niger (latitude 13° 15′N, longitude 2° 18′E, altitude 240 m) on rainfed crops planted on a reddish acid Lambucheri soil classified by West *et al.* (1984) as a psammentic Paleustalf, sandy, siliceous and isohyperthermic, according to the US soil taxonomic system (Soil Management Support Services, 1988) or as an Arenosol by the FAO system (Food and Agriculture Organization of the United Nations—United Nations Education Scientific and Cultural Organization, 1988). Annual rainfall, distributed unimodally between mid-May and mid-September, was 542 mm in 1993, matching almost exactly the long-term mean of 560 mm. Cultivation was done with a traditional hand hoe. Millet cv. CIVT was sown at the onset of the growing season on 14 June; 50 to 100 seeds were placed in each planting hole (pocket) and there were 10 000 pockets per hectare. At 18 days after planting (DAP), the plants were thinned to three per pocket. The field had previously been cultivated for three years, after eight years of fallow, and no mineral fertilizers were applied. These factors led to considerable variation in crop growth, ideal for instrument calibration. The other test crops were a local sprawling cowpea cv. Sadoré Local grown at 40 000 pockets per hectare, groundnut cv. 55–437 sown at 80 000 pockets per hectare, weed populations growing close to millet fields, and different mixtures of grasses on natural pastures. The cowpea and groundnut crops were sown on 22 July. After reflectance measurements had been taken, plant materials were clipped at ground level and dried to constant weight at 65°C.

Calibration of the instrument and validation for growth analysis

At 30 and 40 DAP the millet field was weeded and weeds removed manually to avoid any confounding absorption of radiance by weed biomass. Subsequently reflectance readings on 48 (after the 30 DAP weeding) and 52 individual pockets (after the 40 DAP weeding) were recorded, followed by a harvest of the shoot biomass. For cowpea, the same measurements were taken at 37 and 50 DAP. To examine the usefulness of the reflectometer at different plant densities in the patchy field, at the first sampling date 50 observations were taken, of which 30 contained one pocket and the others between two and four pockets in the instrument's field of view. The second sampling comprized 50 observations of single pockets only. In groundnut, which varied in colour from dark green to yellowish green, 20 observations of single and 11 of multiple pockets were taken at 37 DAP.

In the weeds 52 measurements were taken and in the grass 57. For each sample, observations were made on species composition and stage of development. The ground around the sample areas was cleared of all vegetation before reflectance measurements were taken to avoid border effects.

After shoot dry matter had been plotted against the respective NDVI values, regression coefficients were computed using a linear or logarithmic model for each species or species mixture and each date of measurement. For millet and cowpea, regression coefficients were compared between measurement dates.

A validation study was performed in which the instrument was used to estimate the shoot biomass at 23 and 44 DAP for four cultivars of millet in a factorial experiment with various combinations of millet crop residues applied as surface mulch and with broadcast or placed phosphorus application. Measurements were taken from five and seven pockets per plot. The NDVI was computed, averaged across sub-samples and transformed into dry matter data using the reversed calibration equations. Both measured and calculated data were subjected to analysis of variance. Means of the different phosphorus fertilizer treatments were plotted to see whether, with destructive harvests at the thinning and booting stage of plant development, a realistic growth curve could be established, and whether treatment differences could be reliably detected.

Regressions and analyses of variance were performed with the statistical package GENSTAT 5 (Lawes Agricultural Trust, 1987).

RESULTS

For millet, the experimental data from both planting dates fitted a simple logarithmic model well (Fig. 2). The regression analyses showed different intercepts of the two lines ($p \leq 0.1\%$), but there was no indication of a difference in slope. Despite being on a logarithmic scale, the regression analysis was sensitive to odd values for extremely small plants. Thus one data point from a pocket with a shoot dry matter of only 0.1 g m^{-2} was excluded from the analysis.

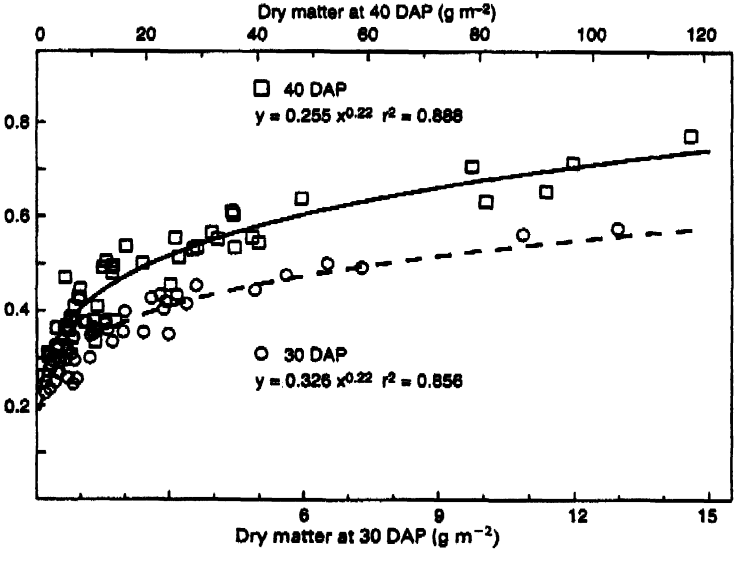

Fig. 2. Relations between the normalized difference vegetation index (NDVI) computed as NDVI = [(NIR − R)/(NIR + R)] and shoot dry matter of millet at 30 (○) and 40 (□) days after planting (DAP).

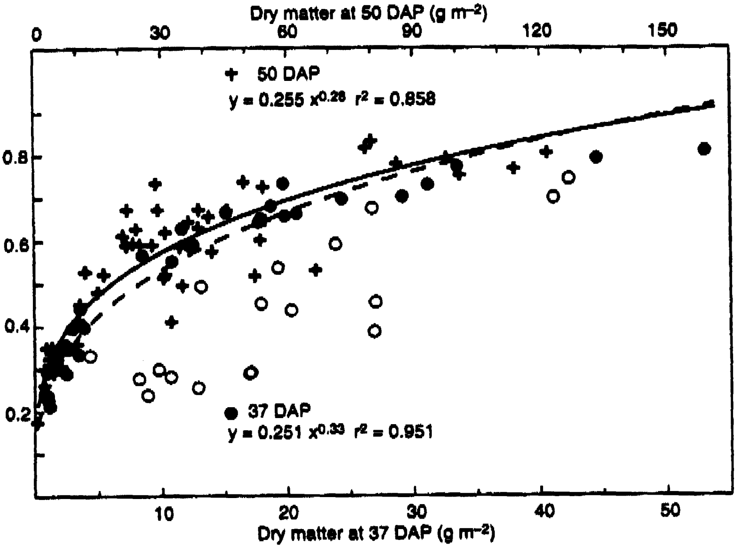

Fig. 3. Relations between the normalized difference vegetation index (NDVI) and shoot dry matter of cowpea at 37 (●) and 50 (+) days after planting (the open circles are measurements from several pockets in the field of view of the reflectometer; the regressions are based on observations with only a single pocket, ● and +).

For cowpea, fitting NDVI data to shoot dry matter was only successful when measurements of more than one pocket per observation were excluded. Again logarithmic models were found to be suitable but, in contrast to millet, slopes were different for the two sampling dates (Fig. 3). For groundnut, relationships between NDVI and shoot dry matter were unsatisfactory, irrespective of the number of pockets per observation (Fig. 4).

For both species mixtures, weeds and grass swards, correlations between NDVI and dry matter were only partially satisfactory and depended to a large degree on the homogeneity of the mixture (Fig. 5a and b).

When millet was grown at different fertility levels, sensible growth curves could be constructed by combining data from the harvests with that from the non-destructive estimations of shoot dry matter production (Fig. 6). It was thus possible to establish full growth curves for this crop using an experimental area 25% smaller than would have been needed using destructive harvesting alone.

DISCUSSION

Given the sparse planting density of millet and the limited plot size of many experiments, simple non-destructive biomass estimates made with a cheap radiometer could be of great value. Frequent NDVI measurements, especially

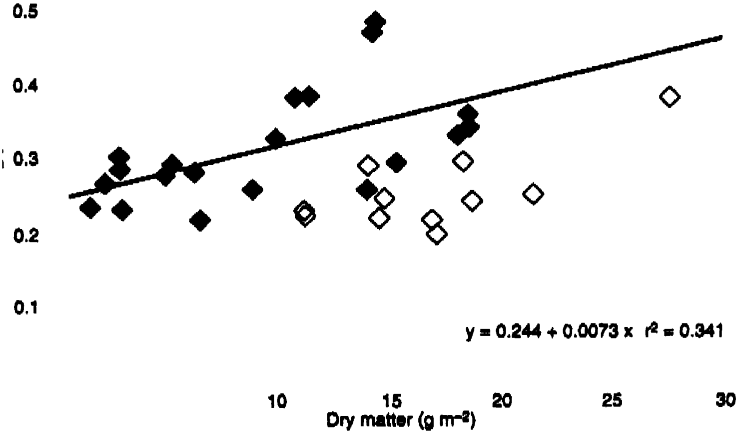

Fig. 4. Relations between the normalized difference vegetation index (NDVI) and shoot dry matter of groundnut at 47 days after planting, where ◆ are measurements from a single and ◇ from several pockets in the field of vision of the reflectometer. The regression is based on observations with only a single pocket.

during the exponential growth phase between thinning and flowering, would enable precise growth curves to be established. Thus one could go beyond destructive time series growth analyses towards comparative growth models. However, the difference in intercept between the two regressions shows that, at least in the initial stages of modelling, separate calibration is needed for each date on which reflectance measurements are taken. The decrease of the slope with increasing shoot biomass also points to the risk that for larger plants small errors in reflectance measurements might translate into major errors in biomass estimation. Taking this into account, the data for growing millet indicate that despite its rapidly increasing leaf area index and consequent overlapping of leaves, the shoot dry matter of this crop may be accurately estimated with a reflectometer, at least in cropping systems with low plant densities. For young millet plants before stem formation, reflectance measurements might also be used to estimate leaf area from biomass using the simple non-linear equation:

$$\text{leaf area} = 162.84 \times \text{leaf mass}^{0.687}$$

derived by Payne *et al.* (1991).

In our study, the slopes of the regressions of NDVI on biomass in millet remained constant across the two measurement dates. This strongly implies that although the plant canopy increased in size, the relative differences in canopy structure between plants of different biomass remained similar between the first date and the second. This finding could lead to a simplification of growth

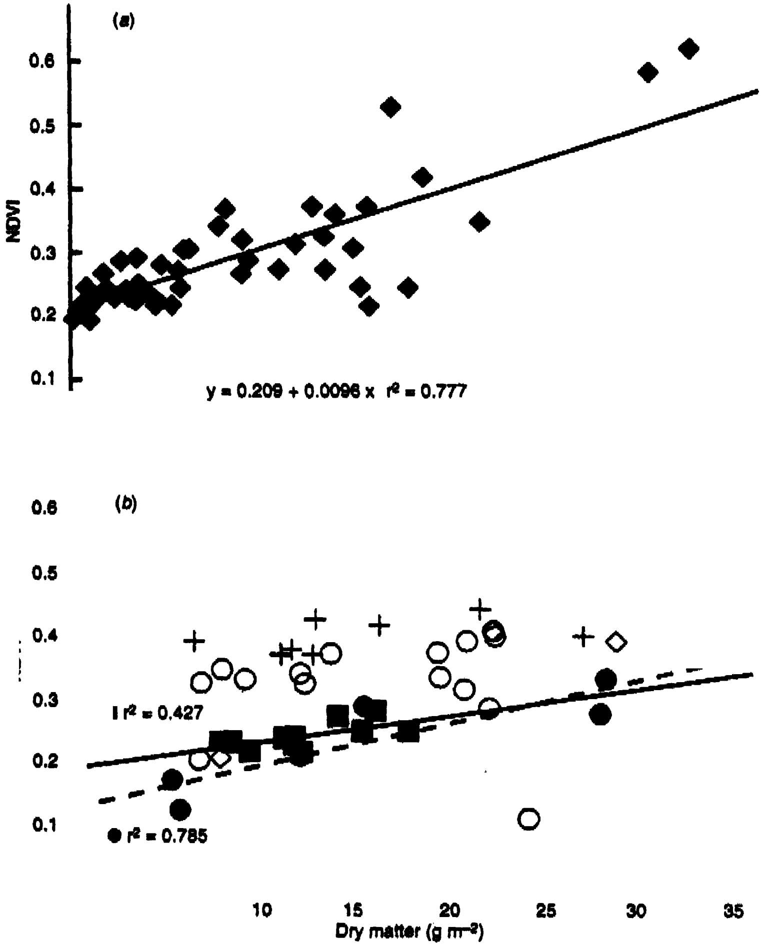

Fig. 5. Relation between the normalized difference vegetation index (NDVI) and shoot dry matter of (a) weeds and (b) grasses. Dominant species in the grass mixtures were: + *Chloris pilosa*, 35 cm high; ∇ *Cenchrus biflorus* and *Chloris pilosa*, 30 cm high; ○ *Eragrostis tremula* and *Chloris pilosa*, 40 cm high; ◇ *Eragrostis tremula*, 50 cm high; ● *Aristida pallida* and *Chloris pilosa*, 35 cm high; ■ *Aristida pallida*, 35 cm high; and △ *Cassia mimosoides*, *Cenchrus biflorus* and *Aristida pallida*, 35 cm high. The solid symbols (● and ■) mark the species mixtures for which regressions lines are drawn.

simulation models for millet if it was confirmed that other genotypes behave in the same way. Growth could be modelled simply by the changes in the intercept of regression curves without the need to account for differences in slope at each stage of growth.

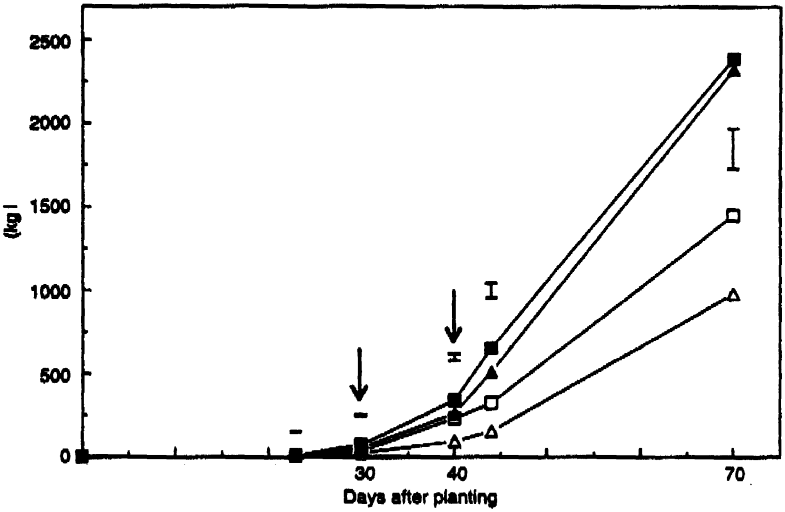

Fig. 6. Destructive and non-destructive determination of millet shoot dry matter on plots with different rates and forms of phosphorus application as single superphosphate. Data points are means of 24 treatment combinations with the same phosphorus fertilization level where: △ indicates the unfertilized control; □ indicates 0.5 kg P ha^{-1} placed with the seed in the planting hole; ▲ indicates broadcast application of 13 kg P ha^{-1}; and ■ indicates broadcast application of 13 kg P ha^{-1} and 0.5 kg P ha^{-1} placed with the seed in the planting hole. Vertical bars show standard errors of the difference. Results at 30 and 40 DAP, marked by arrows, are based on reflectance measurements whereas all other data were determined by destructive harvests.

In the case of cowpea no such simplification was possible. Slopes of the regressions of NDVI on shoot dry matter were different for the two measurement dates, indicating that the canopy structure had changed, probably because of the sprawling habit of the genotype used. The results for cowpea, which showed a similar correlation between NDVI and shoot dry matter to that found by Nageswara *et al.* (1992) in groundnut, also indicate the limitations of using a single pair of vertically positioned diode sensors to capture reflected light. Changing the position of the sensors above a plant led to variation in the NDVI values, indicating that the sensitivity of a sensor decreases towards the edges of its field of view. A series of sensors mounted along a horizontal beam might lead to an overlapping and more homogeneous capture of incoming radiation from different angles and thus provide a better estimation of NDVI.

The relation between NDVI and shoot dry matter for single pocket measurements in groundnut was too small for the regression equation to be of use in non-destructive growth measurements. The poor correlation may have been caused by the fact that the measured plants varied widely in their leaf colour. This variation is common in the Sahelian environment, where deficiencies of nitrogen, phosphorous and molybdenum, in combination with aluminium toxicity and biotic stress factors, such as nematodes, lead to particularly large variability in groundnut growth. Under more homogeneous experimental conditions it might be possible to obtain more accurate estimations of biomass for this species using a radiometer.

The colour of the vegetation is probably also a major determinant of the accuracy of this technique when applied to weeds and natural grasses. In this study, the correlation between NDVI and dry matter in weeds was in the same range as that found by Mitchell *et al.* (1990) for alfalfa. However, the homogeneity of the species and hence of the reflected light may well have affected the results. Thus if biomass is to be accurately estimated, NDVI data from areas with many dark, broad-leaved species may require a different calibration curve from those areas supporting mainly monocotyledonous species.

In the case of grasses, not only the species but also the stage of growth may affect the colour of the canopy and hence the accuracy of the dry matter predictions. At the time of measurement in late August and early September some species had already reached their generative phase of growth while others were still fully vegetative. Acceptable fits were obtained only for the homogeneous small sized green plants and for the ripening mixture of monocotyledons. Similar problems, in which senescent tissue in grass swards led to different light absorptions, have been reported by Mayhew *et al.* (1984). Tucker (1979) found a coefficient of determination of 0.42 between the NDVI and total dry biomass of blue gramma grass (*Bouteloua gracilis* (H.B.K. Lag)) at the late growth stage when only half of the biomass was still green. This is very similar to our result for *Aristida pallida* (Fig. 5b). To improve estimates of biomass from reflectance measurements Asrar *et al.* (1984) proposed fitting separate regression functions to dead and photosynthetically active parts of the phytomass. However, this required a laborious separation of the material.

While the sensitivity of reflectance measurements to photosynthetically inactive tissue might cause considerable distortion in shoot dry matter estimation, it is advantageous when damage to physiologically active plant parts has to be quantified. Thus, in the assessment of the severity of foliar diseases on groundnut (Nutter, 1989), or of partial burial by sand blasting (Michels *et al.*, 1993), reflectance measurements might provide physiologically more relevant information than a conventional destructive biomass determination.

Improvements which could be made to the apparatus used in this study include provisions to allow the measurement of near-infrared and red reflectances simultaneously, automatic calculation and recording of NDVI values, automatic integration of NDVI values over extended areas, and the addition of some kind of optical system to increase the precision of measurement for sprawling and narrowly spaced row crops.

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