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ESTIMATION OF SPATIAL VARIABILITY IN PEARL MILLET GROWTH WITH NON-DESTRUCTIVE METHODS

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SUMMARY

Growth variability in pearl millet (*Pennisetum glaucum*) over short distances is a severe constraint on the interpretation of agricultural experiments in the West African Sahel. The purpose of this study, therefore, was to compare different non-destructive methods to estimate, spatially, millet growth and final yields. Aerial photography, georeferenced radiometric measurements and a chlorophyll meter were tested during three rainy seasons in a nitrogen rate × density × genotype experiment in western Niger. For the radiometric measurements, normalized difference vegetation indices (NDVI) obtained and calibrated for individual millet hills spaced 1.5 m apart were aggregated for the entire experiment with 6000 samples per hectare. A simple calibration procedure was used to correct for variation in soil background reflectance and incident light. For NDVI measurements of individual planting hills, the correlation between plant total dry matter (TDM), leaf weight, leaf area and NDVI was high ($r^2 = 0.89$–0.91) and regression parameters were genotype-specific. Aggregated georeferenced NDVI measurements at the plot level correlated with grain and TDM at harvest ($r^2 = 0.40$–0.87). The analysis of true-colour and infrared aerial photographs permitted the monitoring of millet growth and the quantitative evaluation of treatment responses throughout the growing season. The infrared images were the most efficient in the detection of vegetation followed by the normalized green band of true-colour images. The red band was the least effective because of the influence of soil albedo and image vignetting. Although chlorophyll meter measurements reflected relative differences in plant nitrogen status between treatments, their interpretation required destructive sampling and proved unsuitable to predict millet yields. The results demonstrate the potential of georeferenced radiometric data and aerial photographs to improve soil sampling strategies, sequential plant growth monitoring and the statistical design and analysis of experiments. By providing intermediate data sets, the tested tools can also help in the upscaling of ground truth to satellite data in yield prediction studies.

INTRODUCTION

Spatial variability of millet growth

Pearl millet (*Pennisetum glaucum*) is the most important staple crop of the West African Sahel. It is grown mainly on acid sandy soils with very low levels of mineral nutrients. The uneven distribution of nutrients leads to a high spatial variability in plant growth (Stein *et al.*, 1997). Several studies have attempted to explain the cause-and-effect relationships between the short distance differences

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in millet yield and soil chemical, physical and morphological properties (Geiger and Manu, 1993; Gérard and Buerkert, 1999; Manu *et al.*, 1996). Other authors have investigated previous land use effects on plant growth (Buerkert *et al.*, 1995). With the recent interest in site-specific management and precision agriculture (Moran *et al.*, 1997), there has been a growing interest in high-resolution remote sensing of vegetation, but most of the research has concerned temperate agriculture and full-canopy crops. Unlike most temperate crops, pearl millet fields in the Sahel constitute a clumped vegetation with incomplete soil cover even at maximum biomass development (Bégué and Myneni, 1996). They require, therefore, methodological approaches different to those developed for the study of closed canopy crops.

Remote sensing of vegetation

Remote sensing is based on the radiative properties of the observed objects that can absorb, reflect or diffuse incoming solar radiation. The partitioning of the radiant energy (distribution of the solar radiation between diffusion, absorption and reflection) depends on the incident wavelength and the specific properties of the objects on which that radiant energy is distributed (Monteith and Unsworth, 1990). During the last three decades, a large number of vegetation studies at scales ranging from individual plant leaves to sub-continental zones were based on the vegetation radiative properties in the visible and near infrared ranges of the electromagnetic spectrum. The radiative properties of plant leaves are due mainly to pigments (chlorophylls a and b, carotenoids) present in plant tissues and to refraction caused by scattering in the leaf mesophyll structure; green leaves show a rapid increase in reflectance between the red and infrared wavelengths that often is called the 'red edge'. This led to the development of a normalized difference vegetation index (NDVI) equation (Tucker *et al.*, 1985):

$$\mathrm{NDVI} = \frac{(\mathrm{NIR} - \mathrm{RED})}{(\mathrm{NIR} + \mathrm{RED})}$$

where RED and NIR are the respective reflectances in the red and infrared wavelengths.

When switching scale from single leaves to vegetation observations from ground-based, air-based or satellite-based sensors, several parameters interfere with the detection of plant biomass. First, because of incomplete vegetative cover, the canopy reflectance will be a combination of plant and soil background reflectance. The influence of soil background, being directly proportional to the fractional vegetation cover, is important particularly for studies in the Sahel where a complete plant cover by crops or natural vegetation rarely is achieved (Bégué, 1993; Hanan *et al.*, 1997). In addition to the soil background, several parameters influence the radiometric response of a plant canopy. Those parameters are sun elevation and azimuth, the sensor's angle of view and plant-related parameters such as canopy leaf area, plant architecture and plant health as affected by water, nutrient stress, pests and diseases.

The purpose of this investigation was to test the reliability of several non-destructive tools to monitor millet growth at the field scale. To this end, aerial photography, close-range georeferenced radiometric measurements and a chlorophyll meter were used in a three-year nitrogen (N) × plant population density × millet genotype experiment. Particular research goals were to examine (i) how close was the correlation between individual millet hill total dry matter (TDM) and NDVI, and how genotype-dependent was this correlation; (ii) to what degree millet yield correlated with plant canopy cover; (iii) whether radiometric measurements and aerial photography effectively detected treatment effects on millet growth; (iv) to what degree the spatial analysis of ANOVA residuals from non-destructive measurements mirrored the 'natural' heterogeneity of an experimental field; and (v) whether millet leaf-chlorophyll concentration was a good predictor of millet TDM at harvest.

MATERIALS AND METHODS

Site description and experimental design

All non-destructive measurements presented in this study were taken in a three year (1996–1998) experiment planted with rainfed millet each growing season at ICRISAT Sahelian Centre, Niger (13°14'N, 2°17'E, 235 m asl). The soil is classified as an Arenosol or a Psammentic Paleustalf, sandy, siliceous and isohyperthermic (West *et al.*, 1984). The climate of the area is characterized by a unimodal rainy season from June to September and a dry season throughout the rest of the year. The average annual rainfall is 560 mm with high inter-annual variability of total rainfall and onset of the rainy season. For the 1996, 1997 and 1998 seasons, total precipitation was 510, 362 and 720 mm respectively.

The experiment had a factorial structure: three levels of N application × three millet genotypes × two planting densities. Replications were placed into two blocks because a north-south fertility gradient was expected due to different soil series. Nitrogen was applied at rates of 0, 30 and 60 kg N ha^{-1} in the form of calcium ammonium nitrate (CAN) split into two equal doses applied at 34 and 54 days after sowing (DAS). The three millet genotypes had growing cycles of 110 d (Sadoré local), 90 d (Composite Inter-Varietal de Tarna, CIVT) and 85 d (Haini Kiré Précoce, HKP). The two planting densities were 1 × 1 m and 1.5 × 1.5 m. Because the crop establishment was poor in 1997, 4 kg P ha^{-1} as NPK 15–15–15 fertilizer was placed uniformly with the seeds in all plots of the experiment in 1998. Plot size was 15 × 15 m with alleys of 1 m between plots.

Destructive plant measurements

Each year at millet maturity, TDM and grain yield of millet was determined at the plot level. To correlate TDM with hill NDVI measurements taken at 63, 64 and 65 DAS in 1998, 30 millet hills were harvested for each of the three genotypes. The leaves from all plants in each hill were removed and leaf area measured with a LI-3100 Area Meter (LI-COR Inc., Lincoln, NE, USA). Subsequently, plant material was oven dried at 65 °C to constant weight.

Radiometric measurements

During the 1997 and 1998 seasons, radiometric measurements were taken over the experiment with a bicycle-wheel mounted radiometer described by Lawrence *et al.* (2000). The equipment consisted of an odometer and a sensor mounted on a lightweight, single-wheeled handcart. The sensor comprised a red and infrared photosensitive diode, one maximally sensitive to red light of wavelength 660 nm and the other to NIR light of 880 nm wavelength. Electronic circuits read the sensor data, converted them to NDVI values sent through a serial link to a Trimble® Pathfinder ProXL/TDC1 data logger of a Global Positioning System (GPS). To obtain NDVI measurements with sub-metre accuracy, all GPS data were post-processed with reference data from a base station within 2 km distance. In this study, the radiometer was used (i) in 1998, to measure NDVI values of individual millet hills for the three genotypes and to assess whether or not varietal differences existed in the relationship between NDVI and TDM; and (ii) to acquire over the entire experiment, georeferenced NDVI measurements taken every 33.3 mm along millet rows and stored as a single average measurement for every one metre distance, at 50 DAS (1997) and, alternatively, at fixed-distance intervals of 0.9 m at 62 DAS (1988).

As NDVI measurements taken with the radiometer were affected by changes in soil surface water content, cloud cover and incident solar radiation, NDVI measurements were corrected according to the following equation (Lawrence *et al.*, 2000):

$$\mathrm{NDVI}^0 = \frac{\mathrm{NDVI} - \mathrm{NDVI_s}}{1 - \mathrm{NDVI_s} \cdot \mathrm{NDVI}}$$

where NDVI^0 = the soil adjusted vegetation index and $\mathrm{NDVI_s}$ = the NDVI measurement of bare soil.

To minimize the influence of solar angle on reflectance and NDVI (Rondeaux *et al.*, 1996), all measurements were taken in full sunshine between 11.00 and 13.00 hrs.

Aerial photography

Aerial true-colour and infrared photographs were taken from a balloon at low wind speeds or from a kite at high wind speeds (Buerkert *et al.*, 1996; Gérard *et al.*, 1997). To minimize shadows in true-colour photographs, flights were performed between 11.00 and 14.00 hrs. The equipment consisted of a remotely controlled, standard 24 × 36 mm reflex camera (Nikon F 601) with automatic shutter speed adjustment and a 50 mm lens. An altimeter (Robbe Company, Grebenhain, Germany) was used to set the equipment to the required altitude. The emulsions were Kodak GOLD ISO 100 colour negative films and EKTACHROME infrared films (Eastman Kodak Company, Rochester, NY, USA) rated ISO 100. For the

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infrared photographs, a multi-coated yellow-orange glass filter, equivalent to WRATTEN No. 16, blocked radiation below 540 nm wavelength.

False-colour infrared photographs were taken in 1996 at 65 DAS and 96 DAS. True-colour photographs were taken at 96 DAS in 1996, at 50 DAS in 1997 and at 56 and 80 DAS in 1998. For subsequent digital processing, colour negatives and infrared slides were scanned with a Canon slide scanner.

Using the Image Warp extension of ArcView®, all digital images were rectified and registered according to ground control points (nine 0.5×0.5 m white panels placed in the field) surveyed with a differential GPS. All geographic information was projected in the UTM31 coordinate system to allow spatial analysis in metric units.

ArcView® grids were created for every image corresponding to the red, green and blue bands of the photograph. For the infrared images, NDVI grids were computed by using the red grids (infrared reflectance) and the green grids (red reflectance) for each pixel. For the true-colour images, red grids and normalized green grids were used to study the millet vegetation. The green band was normalized by dividing the green band brightness by the total brightness (Ewing and Horton, 1999) as follows:

$$G_N = \frac{G}{G + R + B}$$

where G_N = the normalized green reflectance and G, R and B = the respective reflectances in the green, red and blue bands.

Chlorophyll meter measurements

During the 1996 season, leaf N status was measured with a SPAD 502 chlorophyll meter (Minolta Co. Ltd., Osaka, Japan) at regular intervals (11 series of measurements from 40 to 105 DAS). Following the approach of Bausch and Duke (1996) for maize (*Zea mays*), chlorophyll meter measurements were taken on the newest fully expanded millet leaf at a point approximately half the distance from the leaf tip to the collar and halfway between the leaf midrib and leaf margin. SPAD measurements were taken on representative tillers of 30 hills per plot, averaged per plot and subjected to analysis of variance. In an effort to correlate SPAD readings with true leaf N concentration, in 1996, at 40 DAS, 35 leaves were collected from the different N treatments. The average of ten SPAD readings on each of these leaves was related to leaf N concentration determined with a Macro-N-analyser (Heraeus, Bremen, Germany).

Statistical and geostatistical analysis

For the three growing seasons, analysis of variance was performed on grain and straw yields to estimate treatment effects and treatment interactions. For the hill-centred radiometric measurements, the relationship between NDVI and plant dry weight was analysed with an exponential model using the group regression function of Genstat 5 (Lawes Agricultural Trust, 1993). Simple linear regression

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was used for all non-destructive radiometric and photographic measurements at the plot level and all residuals were tested for normal distribution. Unless stated otherwise in the text, significant differences indicate a probability level of $p < 0.01$.

NDVI grids obtained from false-colour infrared photographs and radiometric measurements, red grid and normalized green grids were aggregated and averaged at the plot level using the Spatial Analyst functions of ArcView®, and tabular data were exported for analysis of variance. ANOVA results of non-destructive measurements were compared with ANOVA results of destructive data at harvest.

Plant growth spatial variability was estimated on a finer grid by creating in ArcView® a 3 × 3 m grid overlay over all experimental plots (900 elements). NDVI grids obtained from false-colour infrared photographs and radiometric measurements, red grid and normalized green grids were aggregated and averaged on the 3 × 3 m grid and exported in a tabular format for analysis of variance. Residuals obtained from the analysis of variance of the non-destructive variates were also imported in ArcView® to obtain spatial maps of the residuals. To study spatial variability and spatial dependence of plant growth, the semi-variance (ϒ) of the residuals was estimated according to the following equation (Journel and Huijbregts, 1978):

$$\gamma = \frac{1}{2N(h)} \sum_{i=1}^{N(h)} [z(x_i) - z(x_i + h)]^2$$

where $N(h)$ is the number of experimental pairs $[z(x_i), z(x_i + h)]$ of data separated by the vector h, with h ranging from 0 to half field size (50 m) by an increment of 3 m. Semi-variograms were estimated using the Kriging Interpolator SA extension version 3.2. of ArcView®.

RESULTS

Straw and grain yields

Nitrogen effects on straw and grain yield were not consistent over the three years of the experiment (Table 1). In 1996, the application of 30 kg N ha^{-1} increased straw yield by 22% and grain yield by 29% compared with the unfertilized control. No further increase in yield was observed with 60 kg N ha^{-1}. For the 1997 and 1998 rainy seasons, however, N application did not affect millet yield at any level of application. Differences in grain and straw yields between genotypes were large and consistent over years, with the landrace millet out-performing the short-duration genotypes CIVT and HKP. At the higher planting density, straw yield was significantly greater in all years, but density effects on grain yield were only significant ($p < 0.05$) in 1997 and 1998. None of the treatment interactions was statistically significant ($p < 0.05$) for any of the three years.

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Table 1. Effects of plant density, nitrogen application and genotype on millet straw and grain yields in 1996, 1997 and 1998.

	Density		Nitrogen (kg ha^{-1})			Genotype		
Year	High†	Low‡	0	30	60	Landrace	CIVT	HKP
				Straw yield (kg ha^{-1})				
1996	1949	1532	1499	1829	1892	2153	1542	1525
1997	695	404	482	603	563	661	536	451
1998	1624	887	1178	1384	1205	1611	1217	938
s.e.	105.7			129.4			129.4	
				Grain yield (kg ha^{-1})				
1996	863	814	685	885	944	1150	639	725
1997	331	210	265	284	262	334	236	242
1998	560	298	404	438	446	478	431	379
s.e.	36.1			44.2			44.2	

†plant spacing of 1.0 × 1.0 m
‡plant spacing of 1.5 × 1.5 m

Radiometric measurements of millet

The equation used to correct NDVI for differences in soil background and solar radiation appeared to be more efficient in removing unexplained variability for hills with small millet plants than for hills with large plants. Regression analysis after grouping data by genotype showed that TDM, leaf dry matter and leaf area were highly correlated with $NDVI^0$ (Table 2). The relationships between $NDVI^0$ and millet leaf area, leaf dry matter and shoot TDM per hill were genotype-specific. Differences between genotypes increased with plant size (Fig. 1). Specific

Table 2. Grouped regression parameters for millet leaf dry matter, total dry matter and leaf area of individual millet hills estimated from plant centred normalized difference vegetation index (NDVI) measurements for three genotypes (n = 30 samples per genotype).

	Regression parameters for model $Y = A + B*C^{NDVI^{\circ}}$			
	A	B	C	r^2
Y = Leaf dry matter (g hill^{-1})				
Landrace	−80.0	59.2		
CIVT	−44.6	38.5	7.22	0.89
HKP	−24.1	23.1		
Y = Total dry matter (g hill^{-1})				
Landrace	−69.8	44.3		
CIVT	−60.9	44.1	18.40	0.90
HKP	−22.4	22.3		
Y = Leaf area (cm^2 hill^{-1})				
Landrace	−9648	7112		
CIVT	−5936	4930	9.93	0.91
HKP	−3356	3059		

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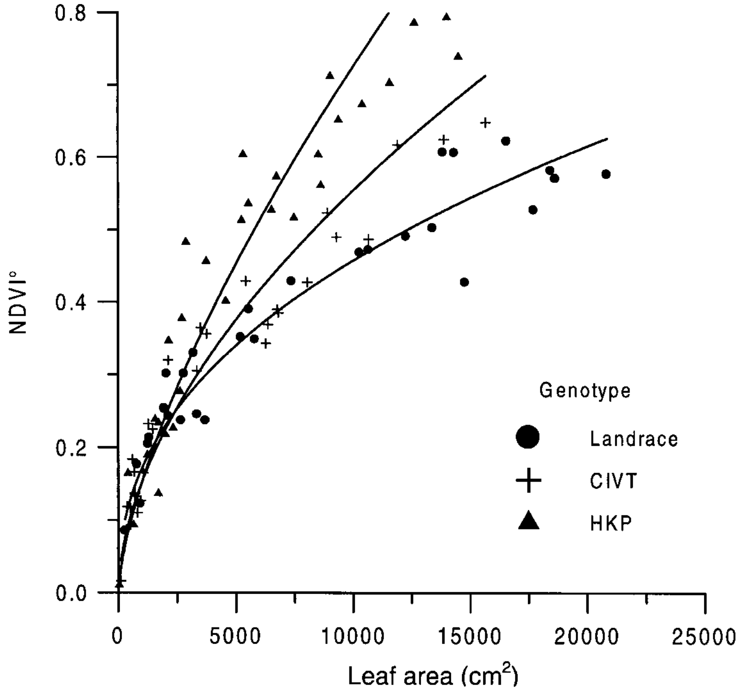

Fig. 1. Relationship between normalized difference vegetation index (NDVI°) and leaf area for radiometric measurements of millet planting hills at 65 DAS (1998 season) in three genotypes (landrace, CIVT and HKP).

leaf area (SLA, leaf area per unit leaf mass) was 163 cm^2 g^{-1} ($r^2 = 0.98$) and was not genotype-specific. At the plot level, the relationship between millet TDM at harvest and average NDVI was linear, with highly significant genotypic differences (Table 3).

Semi-variograms of the residuals on the 3×3 m grid showed a spatial dependence of plant growth of about 30 m (Fig. 2). The spatial maps of the residuals obtained from dense radiometric measurements showed the same general pattern for 1997 and 1998.

Aerial photography

Treatment effects, as detected from vegetation index values derived from infrared and true-colour aerial photographs and averaged at the plot level, closely reflected differences in TDM at maturity (Table 4). In 1996, differences in vegetation indices were significant between 0 and 30 kg N ha^{-1}. Significant differences in genotypes and planting densities were detected for 1996 but varied with the analysed band for 1997 and 1998.

The correlation between plot-averaged vegetation indices (NDVI, red band and normalized green band) and total dry weight or grain dry weight at harvest (Table 5) was significant for all images. No significant differences in regression parameters were observed between genotypes. The highest correlation was

Table 3. Simple linear regression parameters for grain yield and total dry matter of millet predicted from normalized difference vegetation index (NDVI) measurements on 12 August 1997 (54 DAS) and 17 August 1998 (60 DAS) for three genotypes averaged per plot (Y = A + B*NDVI).

	Y = grain yield (kg ha^{-1})			Y = total dry matter (kg ha^{-1})		
Regression parameters	A	B	r^2	A	B	r^2
12 August 1997 reflectometer data (54 DAS)						
Landrace	5	2 586	0.47	25	9 122	0.55
CIVT	−260	3 362	0.77	−919	12 661	0.81
HKP	−103	2 395	0.52	−263	7 731	0.49
17 August 1998 reflectometer data (60 DAS)						
Landrace	104	1 861	0.41	710	8 810	0.40
CIVT	−80	2 379	0.43	−377	10 318	0.87
HKP	10.3	2 021	0.85	−317	10 262	0.78

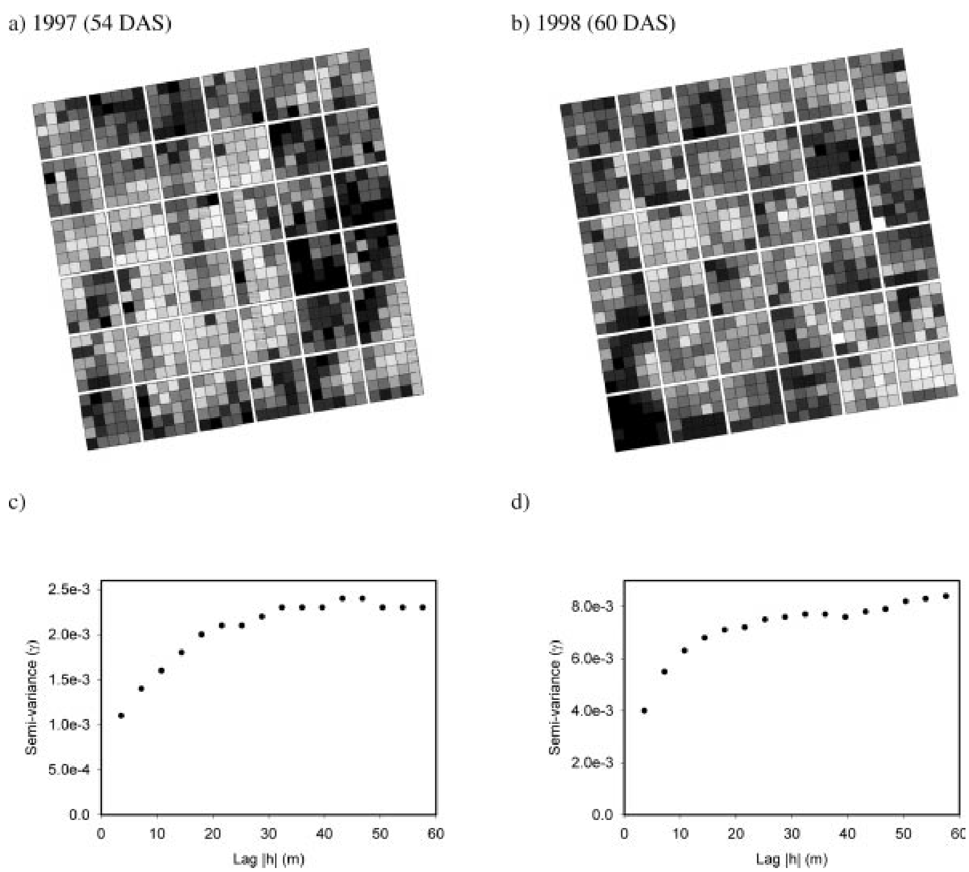

Fig. 2. Map of the residuals obtained from radiometric measurements taken in 1997 at 54 DAS (a) and in 1998 at 60 DAS (b) and averaged on a 3 × 3 m grid showing plant growth variability. Light tones indicate grids with positive residuals (good growth) and dark tones grids with negative residuals (poor growth). Estimated semi-variograms for the residuals are presented for 1997 (c) and 1998 (d).

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Table 4. Effects of nitrogen application, genotype and plant density on millet growth as detected from the analysis of variance of infrared and true-colour aerial photographs.

Image type†	DAS§	Nitrogen‡	F-probability	Genotype	F -probability	Density¶	F-probability
				1996			
IR	65	N3 > N2 > N1	<0.001	Local > CIVT = HKP	<0.001	HD > LD	<0.001
IR	96	N3 > N2 > N1	<0.001	Local > HKP = CIVT	<0.001	HD > LD	<0.001
R	96	N3 = N2 > N1	0.008	Local > HKP = CIVT	<0.001	HD > LD	<0.001
NG	96	N3 = N2 > N1	<0.001	Local > HKP = CIVT	<0.001	HD > LD	<0.001
				1997			
R	50	N2 = N3 > N1	0.027	CIVT > HKP > Local	0.026	HD > LD	<0.001
NG	50	N1 = N2 = N3	0.671	Local > HKP > CIVT	0.093	HD = LD	0.921
				1998			
R	56	N3 = N2 = N1	0.476	Local = CIVT = HKP	0.322	HD > LD	<0.001
NG	56	N1 = N2 = N3	0.847	Local = CIVT = HKP	0.264	HD > LD	<0.001
R	80	N3 = N2 = N1	0.474	Local > CIVT = HKP	0.026	HD > LD	0.004
NG	80	N1 = N2 = N3	0.585	Local > CIVT > HKP	<0.001	HD > LD	<0.001

† IR = normalized difference vegetation index derived from infrared photograph; R = red band of true-colour photograph; NG = normalized green band of true-colour photograph

§days after sowing

‡ For nitrogen treatment N1 = 0 kg N ha^{-1}, N2 = 30 kg N ha^{-1}, N3 = 60 kg N ha^{-1}

¶ HD indicates high plant density (1 × 1 m) and LD low plant density (1.5 × 1.5 m)

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Table 5. Linear correlations between plot average infrared (IR) normalized difference vegetation index, red band brightness (R), or normalized green brightness (NG) and total dry matter (TDM) and grain yield at harvest of millet.

Image type	DAS	r^2 (TDM)	r^2 (grain yield)
		1996	
IR	65	0.50	0.29
IR	96	0.83	0.80
R	96	0.67	0.47
NG	96	0.66	0.60
		1997	
R	50	0.13	0.03
NG	50	0.30	0.45
		1998	
R	56	0.46	0.28
NG	56	0.66	0.41
R	80	0.42	0.16
NG	80	0.67	0.30

obtained for the 1996 infrared image taken at 96 DAS. The correlation between normalized green band and yield data was higher than in the analysis of the red band. This was demonstrated most clearly by the 1998 true-colour image taken at 80 DAS.

Semi-variograms obtained from the 3×3 m aggregation of the 1996 NDVI residuals (Fig. 3) at 65 DAS showed an inflection at 10 m and a linear trend from 10 m to 50 m. The semi-variogram slopes were greater for the red band than for the normalized green band.

Chlorophyll meter

The analysis of variance for the eleven series of chlorophyll meter measurements showed significant effects of N, plant density and genotype on SPAD readings. Genotypic differences in SPAD meter readings (Fig. 4a) did not always indicate differences in the plant N status but, possibly, differences in optical properties of the leaves. SPAD readings also allowed detection of density effects on leaf N status (Fig. 4b). These effects became highly significant from 64 DAS until the end of the season. Nitrogen effects on SPAD measurements were significant only between 0 and 30 kg N ha^{-1} from 74 DAS until the end of the growing season (Fig. 4c). Similar SPAD readings were observed at 30 and 60 kg N ha^{-1}. Significant differences in SPAD readings due to genotype were also recorded in 1997 and 1998. The relationship between leaf N concentration at 40 DAS and SPAD readings was highly significant ($p < 0.001$, $r^2 = 0.40$), but no genotypic differences in SPAD-leaf N concentration could be detected. Correlation between SPAD readings at the plot level and millet grain yield and TDM yields was low throughout the growing season ($r^2 < 0.15$) in all years.

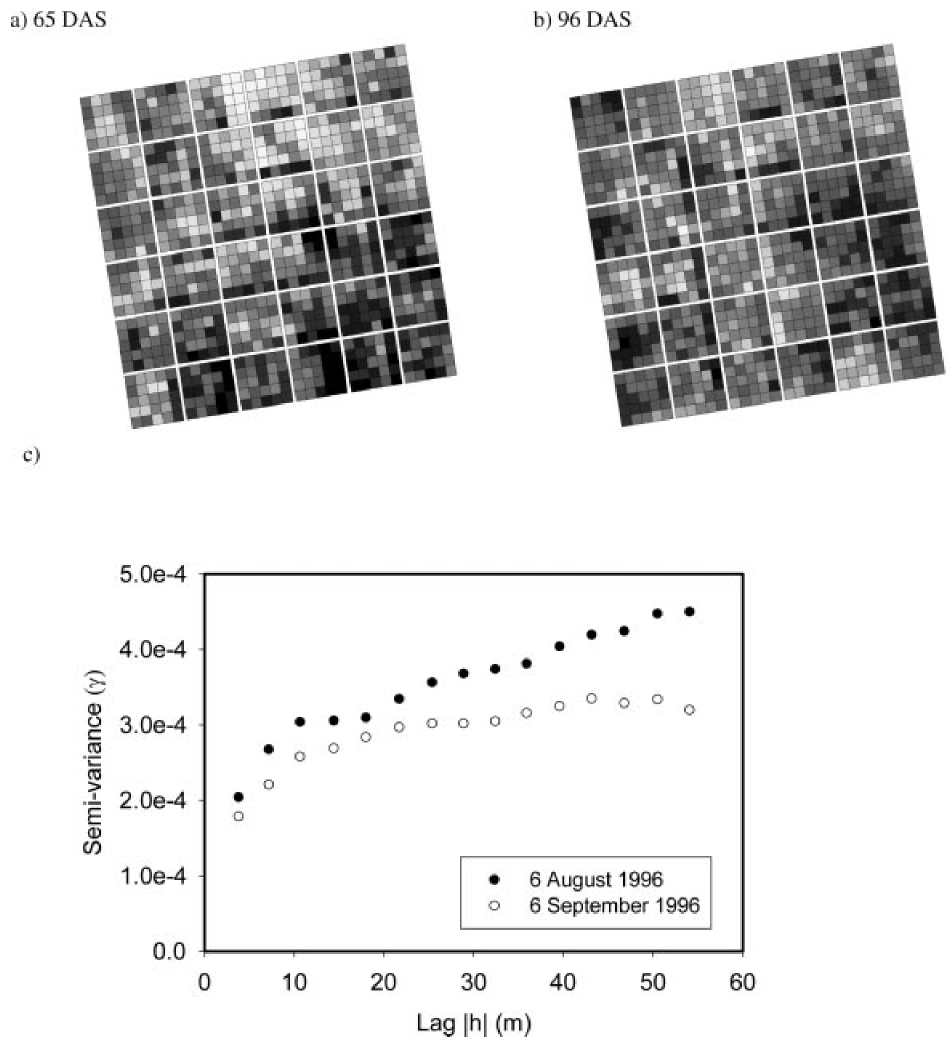
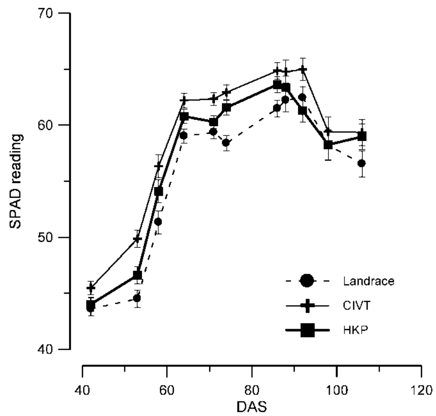


Fig. 3. Map of NDVI residuals derived from false-colour infrared photographs taken in 1996 at 65 DAS (a) and 96 DAS (b) and the resulting semi-variograms of the residuals (c). Light tones indicate grids with positive residuals (good growth) and dark tones show grids with negative residuals (poor growth).

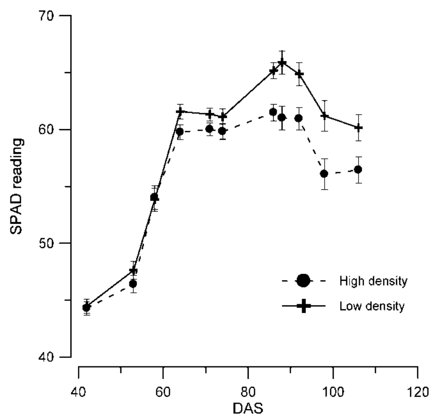
DISCUSSION

Previous studies on Sahelian soils showed a spatial dependence of soil chemical properties similar to the one detected from radiometric or photographic measurements in this study (Beckers, 1997; Stein *et al.*, 1997). To the authors' knowledge, however, this is the first study on the use of a GPS-based radiometer for such measurements in the Sahel. Under the spatially variable crop growth conditions of such an environment, the easily collectable radiometric data could also be used for cokriging in studies of spatial changes in soil chemical and physical properties (Atkinson *et al.*, 1992).

a)



b)



c)

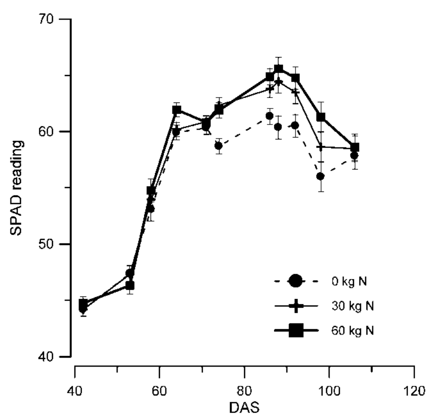


Fig. 4. Effects of genotype (a), plant density (b) and mineral N fertilizer (c) on Minolta SPAD meter readings at eleven dates during the 1996 season (vertical bars indicate *s.e.* of means obtained from the ANOVA for each date).

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Soil adjusted NDVI values from the wheel-mounted radiometer showed greater scatter for larger plants than for smaller plants. The greater variation for large plants seemed to be caused partially by the simplifying equation used for the soil background correction that assumed an NDVI = 1 over dense vegetation. Since no calibration measurements were taken over full vegetation the validity of this assumption could not be verified with this data set. Measurements of individual planting hills of the three millet genotypes with the radiometer indicated the need for genotype-specific calibration curves in the estimation of millet leaf area and dry weight. Genotypic differences in canopy architecture, leaf angle distribution and phenological stages of growth may explain the differences in the TDM-NDVI relationships. A unique property of this radiometer compared with other radiometric tools is the proximity of the sensor to the soil (1.5 m) resulting in a large influence of the vertical dimension of the plant canopy on the reflectance. Genotypic differences in growth stages may also explain why at 65 DAS the early maturing genotype HKP had the steepest biomass-NDVI curve whereas the flattest curve was observed for landrace millet. The use of specific NDVI-biomass curves for each crop growth stage might appear to be a solution for millet biomass-leaf area determinations, but the frequently observed short distance variation in soil productivity causes a wide range of crop growth stages and canopy architectures within a given genotype at any given time.

Plant growth variability maps obtained from radiometric measurements and true-colour photographs were very similar and showed the same vegetation pattern. The radiometer produced a robust data set consisting of over 6000 NDVI measurements per hectare with a position accuracy of 0.2 m. The difference in the semi-variance magnitude between the two years was largely due to the mode of NDVI data acquisition which was averaged over 1 metre distance in 1997, whereas discrete NDVI measurements were taken every 0.9 m for the 1998 data set. The fact that the sill reached 30 m for both years indicates spatial independence of data over that distance.

Calculation of NDVI, red band and normalized green band values averaged at the plot level reflected the treatment effects on crop growth. A poor correlation was observed, however, between NDVI measurements taken several weeks before harvest and at harvest. The lag time in the measurement likely contributed to this fact. However, a note of caution should be added to the interpretation of these statistics as all correlation coefficients depend on the assumption that the residuals from a linear relationship between the two variables considered are independent random variables. Since the correlation coefficients here were based on data from a regular grid, this assumption does not hold (Cressie, 1993).

The higher genetic heterogeneity, the phenotypic plasticity and the longer growth period of landrace millet led to a lower correlation for that genotype compared with CIVT and HKP. In this study, the radiometer calibration procedure, that is setting the NDVI to 0.1 over a white panel and an ex-post-correction with the NDVI measured over the bare soil, was an efficient means to remove changes in soil background reflectance. Due to the design of the radiometer which produced integrated NDVI values, its output did not allow separate readings of red and infrared reflectance to be used in classical soil-adjusted vegetation index equations (Baret and Guyot, 1991; Huete, 1988; Rondeaux *et al.*, 1996). Modification of the equipment permitting reflectance measurements of single bands would allow comparison of the proposed correction equation with other soil-adjusted vegetation index equations over a larger range of soil types.

Analysis of the infrared and true-colour photographs taken on the same day (96 DAS) during the 1996 season and the correlation with TDM and grain yield at harvest (Table 4) indicated that the infrared images were more suitable to detect differences in millet growth than were the true-colour photographs. For a true-colour image, the red band alone proved less useful to analyse millet growth than did the normalized green band. The comparative advantage of the normalized green band was obvious during the 1998 season where soil albedo heterogeneity was more pronounced, specifically in the north-west of the field which had a lower reflectance. The soil albedo heterogeneity was most pronounced on 4 September 1996 when the photograph was taken a few hours after 18 mm rainfall. One additional benefit of the normalized green band compared with the red band was the reduction of shadow and vignetting effects that lead to darker image edges.

The SPAD meter was an efficient tool to detect the effects of mineral N applications and stand density on leaf transmittance in millet. Contrary to studies on maize (Blackmer *et al*., 1994; Ma *et al*., 1996), however, in the Sahelian environment SPAD measurements were of little use to predict pearl millet grain yields or TDM at harvest. This poor predictive ability requires further study. It might be explained, partially, by the large variability in plant growth stage within plots and the existence of other, plant growth-limiting factors in the experiment. Genotypic differences in SPAD readings have been reported for other crops such as rice and maize. An adjustment of chlorophyll meter values for specific leaf weight (SLW) greatly increased the correlation between the SPAD reading and leaf nitrogen content in rice (Peng *et al*., 1993) and maize (Chapman and Barreto, 1997) when analysing several genotypes together.

CONCLUSIONS

The results of this study show the potential of non-destructive techniques to monitor pearl millet growth in a Sahelian environment. The analysis of radiometric data and aerial photographs allows the accurate estimation of millet growth at the plant or plot level. The tools are useful particularly in environments in which spatial plant growth variability is high.

Although the characterization of variability in millet growth at the field level is not of direct interest for subsistence farmers of the Sahel, the investigated tools may be useful for the regular monitoring of field experiments throughout the growing season and for the repeated determination of plant parameters such as leaf area index (LAI) and fractional absorbed photosynthetically active radiation

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(fAPAR) needed in crop growth models. These methods can be used also to improve soil-sampling schemes, for the downscaling of satellite data to predict crop yields, for impact analysis of rural development projects and for the analysis of on-farm experiments where yield estimates are often rather tedious.

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