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Aerial photography to determine fertiliser effects on pearl millet and *Guiera senegalensis* growth

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Abstract

Variability in plant growth is high on most sandy soils of the West African Sahel, often requiring extensive destructive sampling for the reliable estimation of treatment effects. A non-destructive method using aerial photographs and topographic measurements integrated in a Geographic Information System (GIS) was evaluated to determine the effects of organic and inorganic soil amendments on the growth of millet [*Pennisetum glaucum* (L.) R. Br.] and *Guiera senegalensis* J.F. Grmel. Based on aerial photographs, quantitative methods were developed to estimate the dry matter of millet plants and *Guiera* coppices present in the field each year prior to millet sowing. Integrating digital images of both plant species, measurements of the field's topography and a map of the experimental layout in a GIS allowed successful monitoring of the growth of both species as influenced by phosphorus application and the shrub-crop interaction. Regressions between the dry matter of *Guiera* coppices and the canopy area were good (r = 0.76 to 0.93) and permitted the calculation of the individual coppice dry matter for the entire field with fewer than 40 destructive measurements. The information on coppices' positions extracted from the aerial photographs and the topographic grid used as covariates explained a significant proportion of the millet growth variability. The use of these covariates also improved the precision of the analysis of variance of millet dry matter data by reducing the residual sum of squares by as much as 33% in the first experimental year. The study demonstrates the potential of non-destructive measurements integrated in a GIS to improve the collection and interpretation of data from field experiments.

Introduction

Spatial variation of millet growth over short distances can be a major problem for the design, analysis and interpretation of field experiments on acid sandy soils of the West African Sahel (Buerkert et al., 1995a; Wilding and Hossner, 1989) where low availability of nutrients, mainly phosphorus (P), and water severely limit crop growth (Bationo et al., 1992; Rockström and de Rouw, 1997). In principle, standard statistical techniques are available to control environmental gradients at field level. Among these are the blocking of treatments at the design stage of an experiment or the use of soil chemical or physical properties collected at the plot level and used as covariates for the statistical analysis of the data. However, the high 'microvariability' of Sahelian soils with a spatial dependence of 2 to 20 m (Beckers, 1997; Wendt et al., 1993) requires a more flexible approach.

The origin of this microvariability, which may change between years (Brouwer et al., 1993), has been related to a combination of inherent soil physical and chemical factors (Davis et al., 1995; Wilding and Hossner, 1989), to differences in the availability of native soil P (Wendt et al., 1993) and to the short-term residual effects of unevenly applied human and animal waste (Buerkert et al., 1995b). In all cases, however, changes in meso-topography (Geiger and Manu, 1993; Stein et al., 1997) and the presence of shrubs such as *Guiera senegalensis* typically growing in natural

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fallow land and farmers' fields seem to play a major role in the observed crop growth variability (Wezel and Boecker, 1998). Possible explanations for the relatively higher soil productivity around these shrubs are: (i) the accumulation of mineral nutrients and organic carbon from falling leaves; (ii) the capturing of dust high in exchangeable bases (Stahr and Hermann, 1996) and particularly potassium (K) by the shrub canopy which leads to increased P availability (Geiger and Manu, 1993). During the rainy season, *Guiera* coppices will regrow and use the residual moisture for continued growth through the following dry months, thus reinforcing the patchiness in soil productivity for the subsequent crop. Under these conditions, more flexible techniques such as covariance analyses with residuals obtained from visual plant scoring (Buerkert et al., 1995a; Gandah et al., 1998), nearest neighbour analyses (Cressie, 1993; Vollmann et al., 1996) and kriging techniques have been found to be more effective in separating environmental from treatment effects. However, they require a relatively dense sampling grid or the use of stratified sampling methods that are expensive and time-consuming. Therefore, low-altitude aerial photographs (Buerkert et al., 1995b; Gérard et al., 1997) were tested in this study as a quick and inexpensive alternative to conventional sampling methods. The purpose of this non-destructive method was (i) to estimate *Guiera* dry matter from aerial photographs using a small set of destructive ground measurements; (ii) to measure the residual effects of *Guiera* coppices on millet dry matter development and the impact of mineral fertilisers on crop and *Guiera* regrowth; and (iii) to use the information on *Guiera* positions to improve the statistical analysis of millet dry matter data affected by the shrub-crop interactions.

Materials and methods

Site description and experimental design

A multi-factorial split-plot experiment was conducted during the 1995, 1996, and 1997 rainy seasons (June to September) on a sandy, siliceous, isohyperthermic Psammentic Paleustalf (Soil Management Support Services, 1988) or a luvic Arenosol (FAO 1988) near the village of Goberi, Niger (N 12°58′, E 2°50′) with an average total annual precipitation of 600 mm. The chemical characteristics of the top soil at this site were pH_{KCl} of 4.3, C_{org} of 0.2%, P_{Bray} of 2 mg kg^{-1}, N_{min} of 5 mg kg^{-1}, a cation exchange capacity of 0.9 cmol_{c} kg^{-1} and a base saturation of 68%. The 40 main-plot (10 by 10 m) treatments were factorial combinations of four factors (Buerkert et al., 1998) from which those of interest for this study were: millet crop residues (CR) broadcast at the onset of the season on the soil surface as stalks at rates of 500 or 2000 kg CR dry matter ha^{-1}; nitrogen (N) at 0 or 30 kg N ha^{-1} as calcium ammonium nitrate (CAN) applied in two equal applications at thinning (25 days after sowing, DAS) and booting (50 DAS); and P at 0 kg P ha^{-1} (control) or applied at an annual rate of 4 kg ha^{-1} placed with the seed as single superphosphate (SSP_4), broadcast annually at 13 kg ha^{-1} as SSP (SSP_{13}), broadcast as 'soft' Tahoua rock phosphate (TRP) at a 3-yearly rate of 39 kg ha^{-1} with and without seed placement of SSP (TRP_{39} and TRP_{39}+SSP_4). The four sub-plot (5 by 5 m) treatments randomly assigned to each main-plot were: continuous millet, millet after cowpea (*Vigna unguiculata* Walp.), cowpea after millet and millet intercropped with cowpea. For this study only the two sub-plots sown solely in millet in each particular year were used.

Non-destructive measurements

Photographs

True colour and infrared aerial photographs were taken of the experiment at a height of about 400 m from a balloon or a kite as described by Gérard et al. (1997). To estimate the dry matter of *Guiera* coppices and to test the effects of the different soil amendments on *Guiera* regrowth over the three years, a first series of photographs was taken during the dry seasons of 1995–1996 (November), 1996–1997 (January) and 1997–1998 (January). A second series of photographs was taken at two dates during the 1995 rainy season (28 July and 1 September), to estimate the millet growth response to the different treatments and to assess the influence of *Guiera* coppices on millet growth. To ensure proper georeferencing of the images, white panels of 0.5 by 0.5 m were placed at the four corners of the experiment. Differentially corrected Global Positioning System (GPS) positions of these panels were taken with an accuracy of ± 0.2 m (Trimble, 1996). Photographs were geometrically corrected and georeferenced in ArcInfo$^{(R)}$ using these GPS control points. The *Guiera* positions and canopy areas detected on true colour aerial photographs were used thereafter to derive dry matter regression equations based on destructive ground-truth data and to define zones of the shrubs' influence on millet growth at the sub-plot level.

Topographic measurements and spatial analysis of topographic data

It had been observed from the onset of the experiment that a large part of the microvariability in crop growth was correlated with the topography of the field (meso-topography). Better plant growth was noted on the micro-highs compared to the micro-lows, therefore topographic measurements with a level were taken on the field. Those were performed on a regular grid of 5 by 5 m with additional measurements on the micro-highs. To separate between the meso-topography and the general topographic trend of the field, a median polishing technique as proposed by Cressie (1993) was used. The underlying assumption of such an approach is that the topography under study is deterministic at the larger and stochastic at the smaller scale. On a regular grid, the large-scale structure or trend can be calculated by the sum of the row and column medians and the detrended grid obtained by removing that trend from the topographic grid. As discussed by Jaynes and Colvin (1997), the median polishing method might not capture all of the large-scale trend, and a simple correlation test looking at the detrended grid values *versus* row by column number was therefore added to examine the adequacy of the detrending procedure along rows and columns.

Semi-variograms of both the elevation and the detrended elevation (meso- topography) were calculated in Genstat$^{(R)}$ 5.3 (Genstat, 1993) for four directions (north, north-east, east, south-east) and determine for anisotropy and to examine the detrending efficiency and the spatial structure. The detrended grid was processed using triangulation interpolation to obtain a regular grid of 1 by 1 m which allowed the calculation of average grid values at the sub-plot level. Those average elevation data at the sub-plot level, called detrended topography (DT), were subsequently used as a covariate variable in the analysis of variance of the millet dry matter data.

Destructive measurements of plant growth

Guiera

Each year, after the photographs of *Guiera* coppices had been taken, ten to fifteen shrubs representative of each of three pre-selected shrub size classes were cut, separated into leaves and branches and dried to constant weight at 65°C to determine their dry weight. The exact positions of these shrubs were recorded with a differential GPS.

Crops

Millet was sown in each year at the onset of the rainy season at 10,000 planting holes (pockets) ha^{-1} by placing between 50 and 100 seeds per pocket to 0.05 m depth with a hand-hoe. Pockets were thinned to three plants at 25 days after sowing (DAS), harvested at physiological maturity and the weight of grain, straw and total dry matter determined after oven drying at 65°C.

Image processing

Effects of fertiliser application on Guiera regrowth

The georeferenced true colour photographs taken during the three dry seasons were imported in ArcView$^{(R)}$. As found previously (Gérard et al., 1997), the red band gave the best contrast between shrubs and the sandy soil background (Figure 1a). The red image pixels were segregated into two classes (soil and vegetation) to produce binary data sets. The vectorisation of these binary images then permitted the creation of vector objects representing the shrub canopies in each of the three years. GIS attribute tables for the shrub canopies, including canopy area and perimeter in metric units, were used for subsequent regression against destructively-collected dry matter data. The obtained regression was used in ArcView$^{(R)}$ to obtain shrub dry matter estimates for coppices on the entire experiment. These estimates were aggregated at the sub-plot level. An analysis of variance was performed on the dry matter estimates to study the effect of fertiliser application on *Guiera* regrowth.

Tree-crop interactions

To determine the effects of *Guiera* on millet growth, dry season photographs were used to obtain the centre of gravity (latitude, longitude) for all shrubs in the experiment. Assuming a shrub influence on millet growth of 1.5, 2 and 3 meters radius, circles of these radii were placed around each shrub (Figure 1b). The GIS overlay function was used to split the rings by the sub-plot layout and rings were joined at the sub-plot levels (Figure 1b) to calculate the area percentage of the circles. For notation purposes, the covariates (area percentage of the circles per sub-plot) subsequently used in the analysis of variance of millet dry matter data were called $TA_{1.5}$, $TA_{2.0}$, and $TA_{3.0}$. The vegetation cover inside and outside of the presumed areas

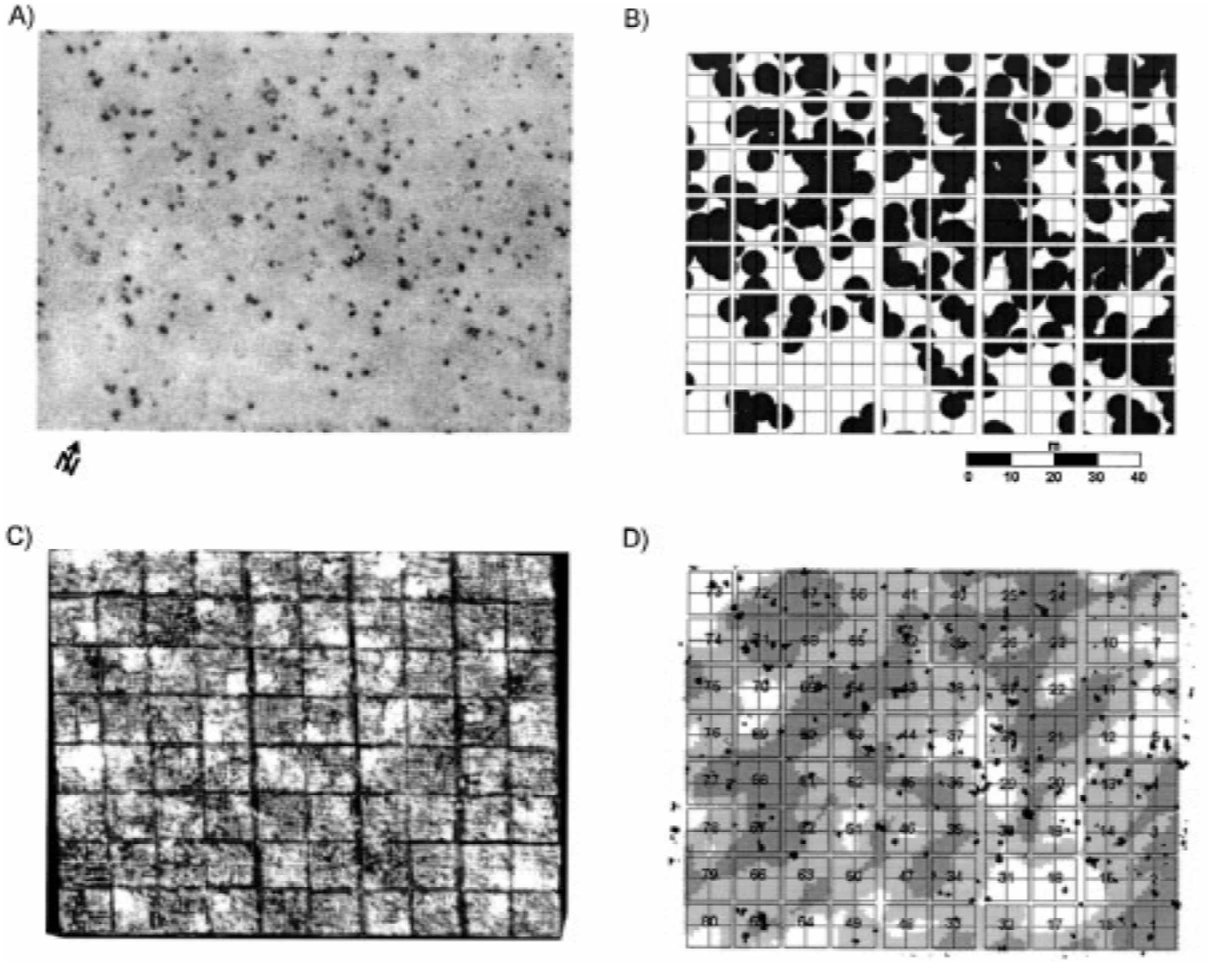

Figure 1. (A) Red band of the true colour aerial image taken in November 1995; (*B*) experimental layout overlayed with a GIS map showing one of the three examined zones of influence of *Guiera* shrubs (3 m radius); (*C*) experimental layout overlayed with a GIS map showing the NDVI image obtained from the September 1995 aerial photograph; (*D*) overlay of the detrended topographical map (darker areas indicate higher meso-elevations) with the experimental layout and the vectorised *Guiera* coppices.

of shrub influence on millet growth was compared using simple pairwise t-tests. Another *Guiera*-derived covariate, tested in the analysis of variance, was obtained by extracting the number of coppices (NC) per sub-plot from the 1995 dry season photograph.

The red band of the 28 July image and the normalised difference vegetation index (normalised ratio of infrared and red bands, NDVI) of the 1 September image (Figure 1c) were classified to binary images (soil and crop vegetation). Pixels classified as vegetation were aggregated at the sub-plot level to obtain a fractional vegetation cover (percentage of the sub-plot cover by vegetation) called FV_{28July} and FV_{1Sep}.

The amount of information added with the covariate was evaluated on the basis of changes in the covariate's F-value, the covariance efficiency factor for the residual term and in the residual sum of squares (rss) in the analysis of variance. Independence between treatments and covariates was tested by a critical examination of the covariance efficiency factor for the treatment terms (Mead et al., 1993).

Results

Non-destructive estimates of Guiera dry matter

A total of 406 bushes were detected in the field from the aerial photograph giving a density of 451 bushes ha^{-1}. For the range of bush sizes studied, the relationship between the canopy area and the foliar and

Table 1. Regression coefficients between the destructively harvested dry matter of single *Guiera senegalensis* shrubs (leaves and branches, y) and the canopy area (m^2, x) computed from aerial photographs in November 1995, January 1997 and January 1998. The regression followed the simple linear equation $y = a + bx$.

	1995		1997		1998	
Sample size	29		28		36	
	Leaves	Branches	Leaves	Branches	Leaves	Branches
a	9	100	96	83	131	105
b	374	292	415	227	239	135
r	0.93	0.82	0.91	0.92	0.92	0.76
DM range (g)	15–1242	133–999	70–1200	36–657	106–858	54–515
Estimated Field DM (kg)	145	150	173	113	104	66

wooden dry matter weight was linear. The fits of the simple regression equation between the destructive leaf and branch measurements of *Guiera* and the canopy area determined from aerial photographs were satisfactory for all years except for branch dry matter in 1998 (r = 0.76; Table 1). There were significant differences between regression coefficients obtained for each year, suggesting inter-annual variability of *Guiera* regrowth morphology. Partitioning between foliar and above-ground wooden dry matter were larger (higher leaf to wood ratio) for 1997 and 1998 compared to 1995.

Treatment effects on Guiera

In contrast to the marked P effects on millet (see below), the analysis of variance on regrowing *Guiera* shoot dry matter did not reveal sizeable effects of the soil amendments on this shrub in any of the years studied. However, given the random distribution of the *Guiera* shrubs on the field and their different sizes across replications, the variation in shrub dry matter per plot was high and may have eventually obscured small treatment effects.

Treatment effects on millet

The correlation between fractional vegetation cover at the sub-plot level and millet dry matter at harvest was highly significant but relatively low (r = 0.69; Figure 2). The poor fit between the non-destructive measurements from the photograph and the ground data can be partially explained by the time lag (one month) between the aerial photograph and the harvest of the experiment. Due to treatment effects and natural variability, millet plants were in different phenological stages one month prior to harvest with some plants growing on less favourable spots being at the pre-tillering stage while the ones on the most favourable spots were already at flowering stage. Leaf area index (LAI) measurements on millet plants in other ICRISAT experiments (data not shown) showed that, a few weeks before harvest, LAI values were ranging from 0.5 to 2.5 from poor to good growing areas of the field.

When the sub-plot data were averaged at the main plot level inside and outside the 3 m influence zone of *Guiera*, millet sub-plot total dry matter (TDM) as determined from the aerial photograph of 1 September nicely reflected treatment effects measured at harvest, except for rockphosphate plots (TRP_{39}) where the vegetation index on the 1 September photograph predicted a much higher TDM (Figure 3). Compared to the control of 2470 kg ha^{-1}, measured TDM increases at harvest were 49% for SSP_{13}, 38% for TRP_{39} and 72% for TRP_{39} +SSP_4.

Effects of Guiera shrubs on millet growth

The analysis of the aerial photographs permitted to detect, at all levels of P application, large positive *Guiera* effects on crop growth as measured by the vegetation indices averaged for P treatments inside and outside the proposed 3 m radius of shrub influence on millet (Figure 3). The comparison of the 28 July and 1 September 1995 infrared images revealed that the effects of shrubs on crop growth were more important early in the season.

Effects of meso-topography on millet growth

Once the primary topographic map (Figure 4a) was corrected with the median polishing technique to subtract large-scale trends (Figure 4b, c), the relationship between micro-highs and the position of *Guiera* shrubs became evident (Figure 1d) with shrubs generally being positioned in higher meso-elevations. As presented in the semi-variograms of topographic data (Figure 5a) and the detrended topography (Figure 5b), the median polishing technique has been efficient in removing large-scale trends. For the spatial analysis of the topographic grid, the semi-variogram was linear with no sill (unbounded) while the semi-variogram of the detrended grid followed the exponential model with a sill at a lag of *circa* 25 meters.

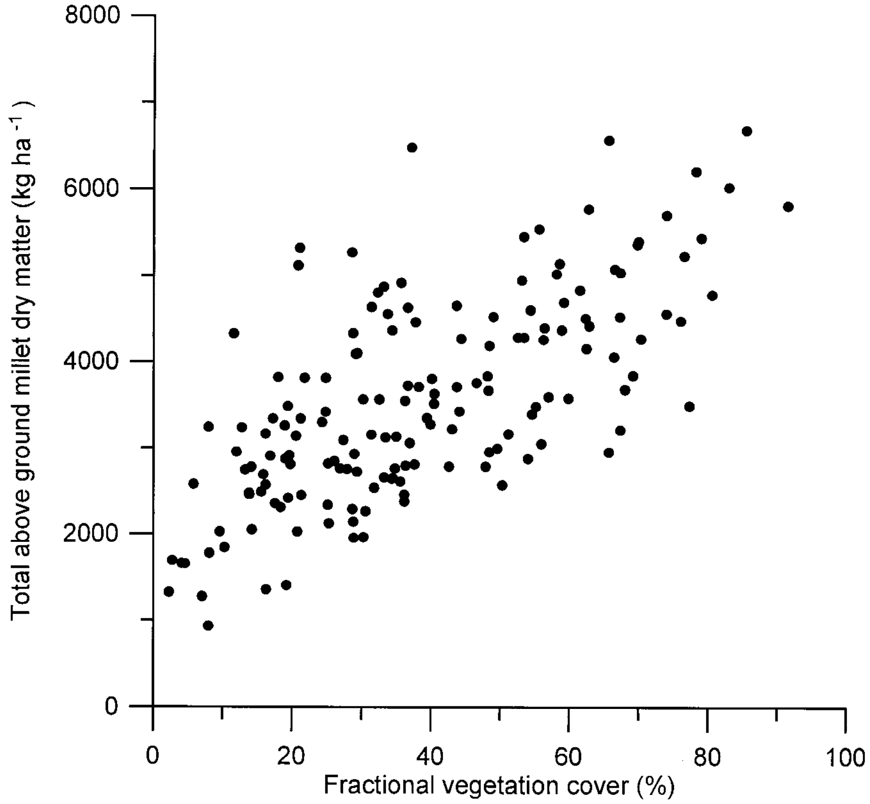

Figure 2. Relationship between fractional vegetation cover (from the 1 September 1995 photograph) and millet TDM at harvest in all 160 sub-plots of the experiment.

Guiera shrub positions and meso-topography versus millet dry matter

Across treatments, the covariance efficiency factors ranged from 0.90 to 0.99, with the lowest values for the crop residue treatment (0.90 to 0.92) indicating almost independence between the treatments and the covariates used. The covariate which best explained the remaining variability in the experiment as measured by the residual sum of squares (rss) was found to be $TA_{3.0}$. For the harvest data, the covariate's effectiveness in reducing rss compared to the analysis of variance without covariate was largest in the first year of the experiment with a 25% reduction for stover and 30% for both grain and total millet dry matter. Across years, variability induced by *Guiera* shrubs and meso-topography seemed to express itself more on grain yield than on stover dry matter (Table 2). As expected, the power of the covariates in explaining total variability decreased over years as treatment effects increasingly masked the initial variability of millet productivity in the field.

The analysis of variance of the fractional vegetation cover for the 28 July 1995 (FV_{28July}) and for the 1 September 1995 (FV_{1Sep}) photographs reflected the dynamic of dry matter variability for that growing season. It also showed that the highest covariate effectiveness was obtained for FV_{28July} with a reduction in rss of 50% and a covariance efficiency factor of 1.94 for $TA_{3.0}$ (Table 2). The comparison of the analyses at the two dates suggested that *Guiera*-induced millet growth variability was more pronounced at early growth stages and levelled off as the crop grew. The use of number of coppices (NC) per sub-plot as a covariate was not as efficient as the other *Guiera*-related covariates but still improved the analysis of variance. The detrended topography or meso-topography average at the sub-plot level, in contrast, did not explain a significant proportion of the variability in the millet harvest data.

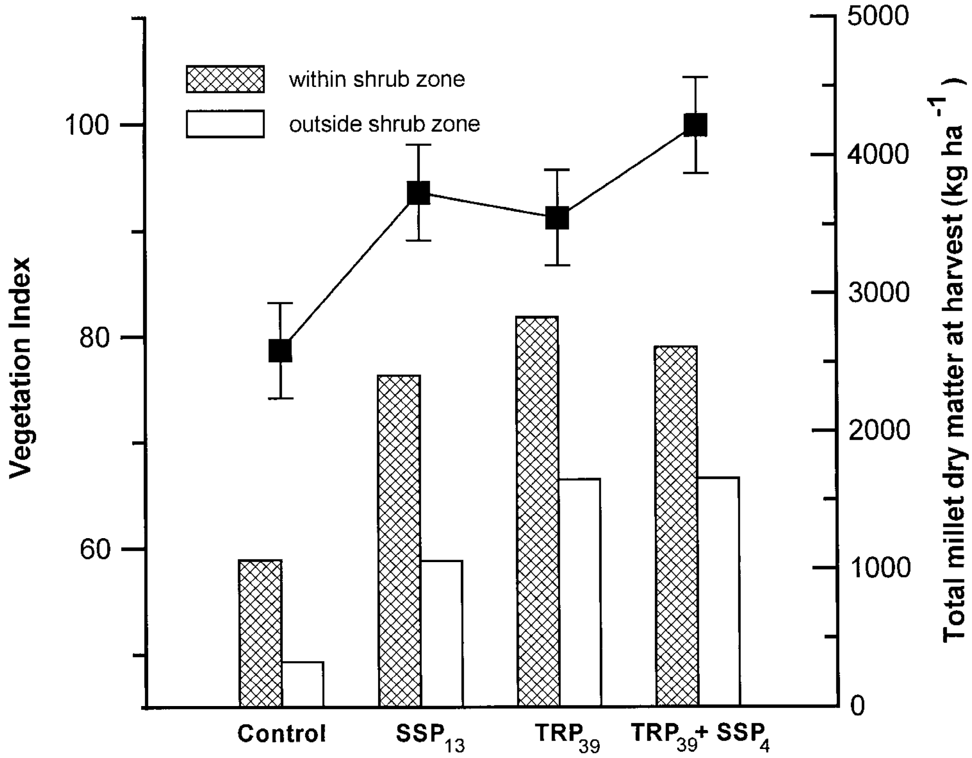

Figure 3. Effects of P fertiliser treatments on pearl millet vegetation index inside (dark columns) and outside (grey columns) a 3 m radius of former *Guiera* shrubs as detected by aerial photographs (1 September) during the 1995 growing season and on total dry matter (■) at harvest (vertical bars represent two standard errors of the difference). Treatments were the unfertilised control (0 kg P ha^{-1}) compared to P broadcast annually at 13 kg P ha^{-1} as single superphosphate (SSP_{13}) and broadcast as 'soft' Tahoua rockphosphate (TRP) at a 3-yearly rate of 39 kg P ha^{-1} with and without seed placement of SSP at 4 kg P ha^{-1} (TRP_{39} and TRP_{39}+SSP_4).

Discussion

Plant dry matter data

The differences in the regression coefficients between years for the *Guiera* dry matter equations reported here could be due to differences in the pattern and total amount of precipitation during the preceding rainy season which may have influenced coppice morphology, the canopy density and the leaf to branch ratio. With a total precipitation of 360 mm, the 1997 rainy season was much drier than the 1995 and 1996 seasons with 500 mm each explaining the smaller shrub biomass production during the 1997–1998 dry season (Table 1). Despite efforts to take photographs with the sun almost at its zenith (11 am to 2 pm), daytime-related differences in the shrub shadow areas may also have contributed to the observed differences in the regression coefficients. The use of near-infrared photography could have overcome this constraint. Given this and previous findings on inter-site variation of regression coefficients for *Guiera* dry matter estimations (Gérard et al., 1997) from aerial photographs, reliable dry matter estimates of bushes seem to require site-specific destructive calibrations each time a photograph is taken. However, the relatively minor effort required for the destructive sampling of 20–40 shrubs allows the subsequent estimation of the dry matter of hundreds of shrubs together with their precise position in the field, a task that would have been very costly and difficult by classical destructive measurements. The annual *Guiera* biomass production as estimated on the 0.9 ha experiment (Table 1) is similar to the figure found by Wezel (1998) for the Hapex site near Sadoré, Niger (leaf DM of 79 kg ha^{-1} y^{-1}) and to the *Guiera* yearly production per shrub reported by Le Houérou (1980) on various Sahelian sites. A reliable estimation of *Guiera* regrowth at a given site can also give valuable information for the study of nutrient cycling processes at the field level, as traditionally the shrubs are cut each year by farmers before the rainy season and either left as mulch, burnt on the field or,

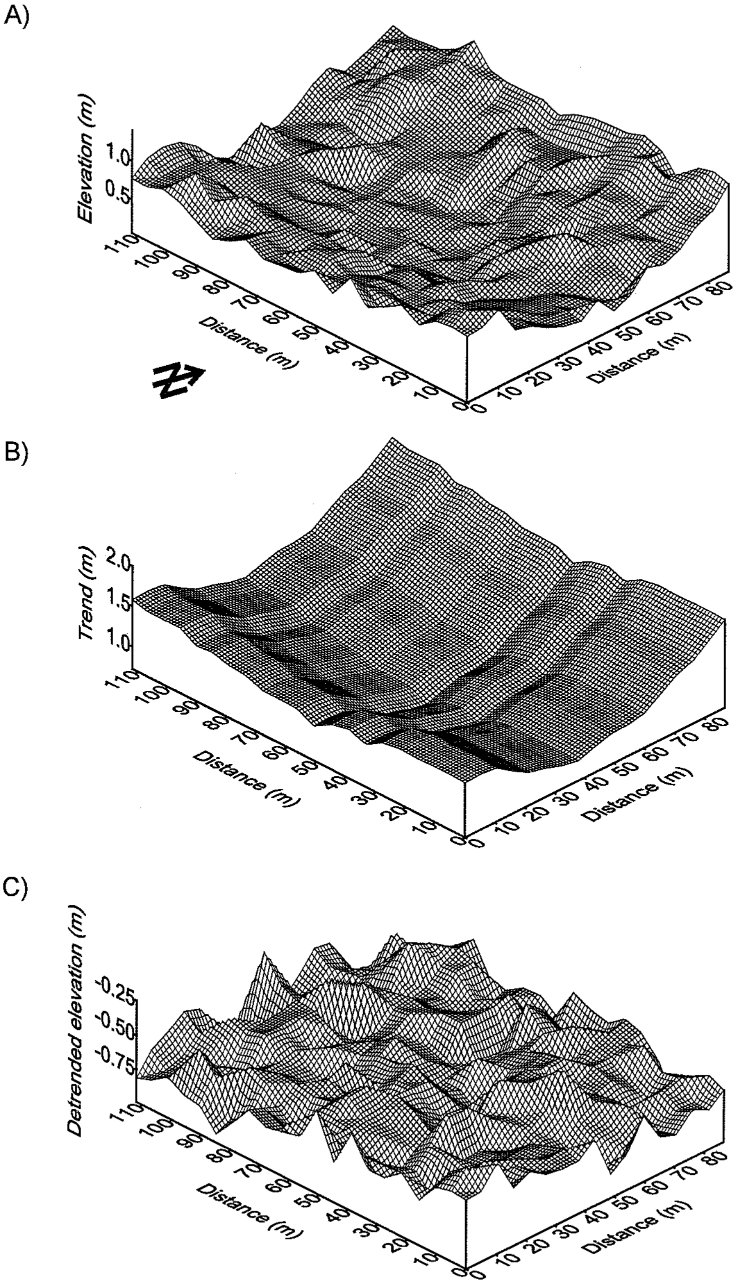

Figure 4. (*A*) Surface map showing the topography of the experimental field from a 5 by 5 m survey grid at the onset of the experiment in May 1995; (*B*) detrending grid obtained by averaging row and column medians of the initial topographic grid for each grid point and used for detrending; (*C*) detrended surface or meso-topography map obtained after subtracting the median grid points from the topographic grid.

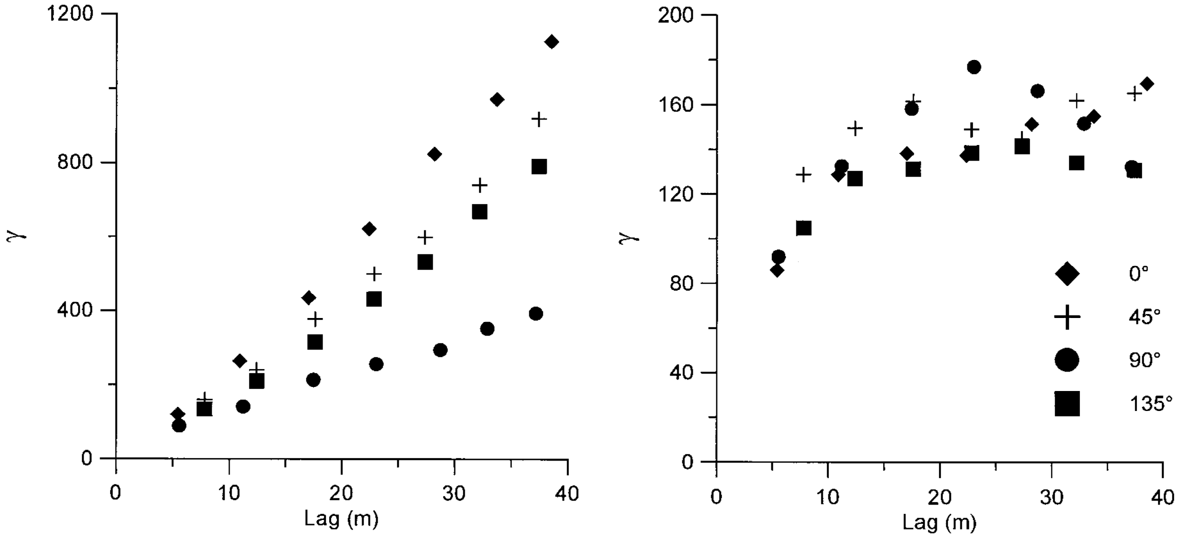

Figure 5. Semi-variograms of the topography grid for (*A*) the raw topographic grid; (*B*) the detrended grid (meso-topography) computed for 4 directions; 0 = north, 45 = north-east, 90 = east, and 135 = south-east.

Table 2. Effect of covariates on the residual sum of squares (rss) and covariance efficiency factor for the fractional vegetation cover (FV) extracted for the 28 July and 1 September 1995 photographs and for the 1995–1997 harvest data (stover, grain and total dry matter, TDM). Covariates are the percentage of sub-plot influenced by *Guiera* coppices assuming a radius of shrub influence on millet growth of 1.5, 2, and 3 meters (TA$_{1.5}$ TA$_{2.0}$, and TA$_{3.0}$), the number of coppices per sub-plot (NC) and the detrended topography (DT).

	Variates for 1995					*Variates for 1996*			*Variates for 1997*		
	FV$_{28July}$	FV$_{1Sept}$	Stover	Grain	TDM	Stover	Grain	TDM	Stover	Grain	TDM
Covariate	Covariate effect on rss (× 10^6)										
Without covariate	0.033	0.052	66	30	150	34	3.5	52	22	2.0	38
TA$_{1.5}$	0.018	0.050	54	24	130	33	3.2	50	21	1.6	32
TA$_{2.0}$	0.018	0.049	53	23	110	33	3.1	50	21	1.6	32
TA$_{3.0}$	0.017	0.045	51	21	100	33	3.0	49	21	1.5	32
NC	0.022	0.051	57	26	120	34	3.3	51	20	1.7	32
DT	0.029	0.049	62	26	130	34	3.4	49	20	1.9	33
Best rss decrease (%)	49	13	25	30	33	3	14	6	9	25	15
Covariate	Covariance efficiency factor for the residual term										
TA$_{1.5}$	1.80	1.03	1.20	1.25	1.30	1.01	1.08	1.03	1.06	1.20	1.15
TA$_{2.0}$	1.84	1.06	1.23	1.30	1.35	1.01	1.09	1.03	1.05	1.21	1.14
TA$_{3.0}$	1.94	1.13	1.27	1.43	1.45	1.03	1.13	1.05	1.03	1.29	1.14.
NC	1.47	1.00	1.14	1.13	1.18	1.00	1.03	1.00	1.07	1.19	1.15
DT	1.12	1.05	1.04	1.15	1.10	0.99	1.00	1.00	1.07	1.01	1.11

in the case of extreme forage shortage, exported from the field to feed animals.

The absence of a significant response of *Guiera* regrowth to P fertiliser application is surprising as these soils are known to be severely P-deficient and showed a large crop response to applied P (Bationo et al., 1992; Buerkert et al., 1998). It may be explained by a deeper rooting pattern of the perennial shrub. Buerkert (1995) showed that deeper layers of the sandy Sahelian soils often remain unaffected by repeated annual application of mineral P. However, as previously mentioned, the unbalanced *Guiera* distribution across treatments and the large variation between replications may have masked small effects of applied P on *Guiera* regrowth.

The overall increase in millet growth around *Guiera* was very marked and confirmed previous findings by Brouwer and Bouma (1997) and Wezel (1998). The improved growth around coppices was more pronounced at the beginning of the rainy season and tended to level off as the season progressed. Similar findings on dynamic changes in the pattern of plant biomass variability within a year were presented by Brouwer and Bouma (1997). A stratification of millet fractional vegetation cover inside and outside the shrub zones (Figure 3) showed that the positive effects of *Guiera* on millet growth were independent of P application, suggesting that improved growth conditions around shrubs were not mainly related to increased P availability as reported by Wendt et al. (1993) but also to the improvement of other soil properties such as available nitrogen, organic matter and pH. Soil analyses by Wezel (1998) along radial transects centred on *Guiera* shrubs showed a very steep decline of improved soil chemical properties (P, N, organic matter) from the shrub centre outwards. Average field levels of these nutrients were reached at distances of 0.5 to 1 m from the shrub centre. In the present study, however, it seemed as if a 3 m radius around shrubs better explained variability in millet growth than a radius of 1.5 or 2 m.

For most years, shrub-millet competition for water during the crop growing season may have been negligible as shrubs are cut to the stumps during the season. Typically, a large part of the shrub water requirement is met by the soil residual moisture after the millet harvest. In a year with very low total precipitation such as the 300 mm of 1997, the positive effect of *Guiera* on millet growth might have been counterbalanced by the competition for water at the end of the growing season. The present data set, however, does not allow the objective evaluation of different components of the shrub-crop relationship.

Non-destructive methods

Although the use of non-destructive measurement techniques to monitor field experiments is not new (Dagnelie, 1981), the recent development of PC-based GIS and image analysis software gives new opportunities for the spatial analysis of data. Non-destructive methods allow spatial analysis of crop growth in a more comprehensive and quantitative manner. Previous studies on *Guiera* (Le Houérou, 1980; Wezel, 1998) relied on destructive sampling of a limited number of shrubs, which may lead to erroneous results when the shrub population is not uniformly distributed across the field under observation. In the present study, the use of non-destructive methods permitted (i) estimation of the regrowth of shrubs over an entire field for three consecutive years with a minimum of field work and the study of the effect of fertiliser application on shrub growth; (ii) study of dynamic interaction between shrub and millet growth at various stages of the growing season; (iii) demonstration of the link between *Guiera* positions and field topography, pointing to the role of the shrubs in building a meso-topography in fallowed fields.

Although it is evident that non-destructive methods cannot replace destructive plant sampling, they are complementary tools that could also be used to design appropriate sampling schemes for subsequent soil and plant analyses.

Conclusions

The presented data allow the critical assessment of the relative merits of non-destructive dry matter measurements in millet and *Guiera senegalensis* on highly variable fields of the West African Sahel. If a high spatial resolution of data is important to determine treatment effects on distinct parts of the field or to monitor shrub-crop interactions, true colour and infrared photographs are effective tools to estimate plant dry matter at the field level and to better monitor crop growth. The covariates derived from *Guiera* coppice positions in the field were valuable means to improve the precision of the analysis of variance of both non-destructive and destructive measurements. If absolute dry matter values are of interest, care should be taken to properly calibrate the data derived from images with a sufficiently large number of simultaneously collected destructive ground data.

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