Nutrient Cycling in Agroecosystems **67:** 167–176, 2003.

Simulated weather variables effects on millet fertilized with phosphate rock in the Sahel

Charles F. Yamoah[1,6,*], Andre Bationo[2], T.J. Wyatt[3], Barry Shapiro[4] and Saidou Koala[5]
[1]International Crop Research Institute for the Semiarid Tropics (ICRISAT), Niamey, Niger; [2]Tropical Soil Biology and Fertility, Nairobi, Kenya; [3]International Livestock Research Institute (ILRI)/ICRISAT, Niger; [4]Natural Resources Programme, ICRISAT, Bamako, Mali; [5]Desert Margins Program ICRISAT, Niamey, Niger; [6]Current address: c/o P.O. Box KA 30740 Airport, Accra, Ghana; [*]Author for correspondence (e-mail: yamoahcf@yahoo.com)

Received 14 March 2001; accepted in revised form 12 February 2003

Key words: Millet, Phosphate rock, Sahel, Simulated weather

Abstract

The Sudano–Sahelian agroecological zone is characterized by low and variable rainfall regimes and P deficiency. The present study complements previous research efforts and the objective was (i) to use the Newhall Simulation Model (NSM) to characterize three ICRISAT research sites, and (ii) to use output of NSM to develop an empirical model to guide efficient use of rainfall and fertilizers. The results show that length of the periods that rainfall exceeded evapotranspiration was larger in Bengou than in Gobery and Sadoré. Total positive moisture balance during the three growing seasons was 85.7 mm at Bengou and 19.7 mm at Sadoré. The model explained 52% of the variability in millet yields based on curvilinear response to P fertilizer, standardized May–June (R_{mj}) rainfall, and the number of wet days in the year (BW_3). Yields appear more sensitive to BW_3 than to R_{mj}. Their respective elasticity coefficients (E_c) were 0.62 and 0.09. Assessment of the model using $R^2 = 0.76$ and the D-index = 0.85 showed reasonable agreement between model estimation and actual field yields. The study demonstrates the application of simulation models as a cost-effective means in terms of time and funds to agronomic research.

Introduction

Pearl millet (*Pennisetum glaucum* (L.) R. Br.) is an important food crop in the Sahelian region, supplying 80 to 90% of Niger's food need (FAO 1993). Its production faces multiple constraints such as poor soils, diseases, weeds, pests and insects, uncertain rainfall and low quality genetic material (Bationo and Ntare 2000; De Ridder and Van Keulen 1990; Christianson et al. 1990; Sivakumar 1990). Among the soil-related problems, phosphorus (P) deficiency is widespread (Bationo et al. 1993; Payne 1990).

Recent studies have shown that current millet yields could be increased significantly with small doses of P fertilizer under Sahelian weather conditions (Bationo et al. 1993; Hafner et al. 1993; Traoré 1974). Although farmers may be aware of the potential benefits of inorganic fertilizers, they are seldom used, because fertilizers are expensive and difficult to acquire. Integrated use of organic amendments and inorganic fertilizers holds promise for the Sahel, in that it combines nutrient supply, efficient use of applied nutrients as well as improvement of soil physical properties.

The high temperatures and low humidities during the growing period in the Sahel lead to high moisture loss through evapotranspiration. Consequently, crop water stress is frequent, resulting in low efficiency of applied inorganic fertilizer. Justification for using rock phosphate as soil amendment in Sahelian West Africa is that it is locally available and therefore, does not compete for the limited foreign currency earnings. Therefore, information on its impact on yields in the moisture-limited Sahelian agroecological zone is needed to develop appropriate management options for increased productivity. The Newhall Simulation

Model (NSM) has been used to map moisture balance status in several agroecological zones in the USA (Waltman et al. 1997). The objectives of this study are (1) to use the NSM to characterize soil moisture conditions at three ICRISAT benchmark sites, and (2) to use output of the NSM to develop an empirical model to guide efficient P and water management. The most useful and practical model should contain few independent variables.

Materials and methods

The study was conducted from 1997 through 1999 at Sadoré (13°15′ N latitude, 2°18′ E longitude), Bengou (11°59′ N, 3°30′ E) and Gobery (12°58′ N, 2°50′ E), three of the four ICRISAT (International Crop Research Institute for the Semi Arid Tropics) benchmark sites in Niger. The site characteristics are presented in Table 1.

The treatment factors of the study were three P sources, four P rates and two P methods of application. The P sources were single superphosphate (SSP), phosphate rock (PRT) from Tahoua and PRK from Kodjari. According to Bationo et al. (1999), PRT has a P_2O_5 content of 28% and neutral ammonium citrate (NAC) solubility ranged from 1.9 to 3.6%; PRK has 25% P_2O_5 and NAC solubility of 1.9 to 2.7%. The levels of P were zero (control plots without P), 20, 40 and 60 kg P_2O_5 ha^{-1}. The study also examined the effects of continuous annual application and residual effects on millet yields. Nitrogen was applied at 30 kg ha^{-1} to all plots. The experimental design was a randomised complete block with four replications. Sub-sub plot size was 50 m^2. Millet cultivar CIVT (110 d), a non-photoperiodic cultivar, was used at a population of 10,000 hills ha^{-1}.

Weather variables used in the analysis were generated by the Newhall Simulation Model developed by Van Wambeke et al. (1992), using mean monthly rainfall and temperature as input variables. NSM has been used in both tropical and temperate environments. However, in the tropics, such as the Sahel, emphasis is placed on rainfall, since the impact of rainfall in terms of amount, distribution and variability on crop production, is usually greater than that of temperature. Outputs of the model include biological windows (BW): BW_1, defined as the cumulative number of days in the year the root zone is dry (below wilting point) and soil temperature exceeds 5 °C; BW_2, the number of days the root zone is wet (between field capacity and permanent wilting point) and soil temperature exceeds 5 °C, and BW_3, the number of days with wet root zone and soil temperature exceeding 8 °C.

SPI, the standardized precipitation index (McKee et al. 1993), is the difference between rainfall for a specified period and long-term, usually more than 30 yr, average rainfall for that period divided by the standard deviation. Detailed descriptions of applications of NSM and SPI are found in Waltman et al. (1997). The SPI and the NSM model are used to estimate preseason moisture conditions in May–June (R_{mj}) and the number of wet days (BW_3) respectively, critical factors in determining the riskiness of non-irrigated cropping systems (Yamoah et al. 2000).

A general model to link yield to climatic factors may take the form: $Y = f(W, M)$, where Y is yield, W is weather and M is management variables. This model was adopted by Cady (1991) to analyse the possibilities for technology transfer in on-farm studies. Cady's approach, which was based on regression models, was combined with outputs of NSM and SPI for the present study. Thus, observed millet yield

Table 1. Mean characteristics of the experimental sites at Bengou, Gobery and Sadoré and description of phosphorus sources.

Characteristics	Bengou	Gobery	Sadoré
Rainfall (mm/year)	700	605	560
Mean temperature (°C)	29	28	29
Elevation (m)	240	240	240
Sand (%)	94	95	94
pH (KCl)	4.3	4.1	4.1
Organic matter (%)	0.20	0.30	0.22
Bray1 phosphorus (mg/kg)	4.0	2.4	2.3
P sources			
SSP	Single super phosphate (P_2O_5 = 20%)		
PRT[1]	Phosphate rock of Tahoua (Niger) (P_2O_5 = 28%)		
PRK[1]	Phosphate rock of Kodjari (Burkina Faso) (P_2O_5 = 25%)		

[1]Bationo et al. (1990).

at the three benchmark sites over three years and fertilized with P from various sources and rates constitutes the dependent variable. Standardized rainfall and temperature values and biological window variables generated by the NSM represent the weather variables and fertilization regime is the management factor in a multiple regression model (Draper and Smith 1966). Elasticity, given by the formula $(dy/dx)*(X/Y)$ where dy/dx is the regression coefficient and X and Y their respective means, was used to determine the relative effect of the independent variables on yield. Principal component analysis (PCA) was used to group the predictor variables that were significantly correlated, usually with correlation coefficient (r) equal to or greater than 0.80 (SAS 1998). Ten randomly selected cases were used for model validation. Agreement between model predictions and actual yields was assessed using the coefficient of determination (R^2) and the D index of agreement (Willmott and Wicks 1980) calculated as: $D=1-[\Sigma(P_i-O_i)^2/\Sigma(|P_i-O\ |+|O_i-O\ |)^2]$, where P_i and O_i are the predicted and observed values, and O is the means of the observed variables. Like R^2, values of the D index lie between 0.0 (no agreement) and 1.0 (complete agreement) and it is more precise than R^2 according to Willmott and Wicks (1980).

Results and discussion

Biophysical aspects of the sites

The study sites belong to the Sudano–Sahelian agroecological zone, characterized by low and variable rainfall. Soils are sandy, with low organic matter levels and are generally deficient in phosphorus. Thus, principal biophysical factors that limit crop yields are nutrient deficiency and insufficient moisture.

Low quality soils may be amended with fertilizers, animal manure and/or compost, as has been previously demonstrated in the region (Bationo et al. 1993; De Ridder and Van Keulen 1990; Christianson et al. 1990). As inadequate moisture supply due to uncertain and low rainfall is difficult to manage, this study places special emphasis on the analysis of preseason weather conditions in May–June (Table 2). The rationale is that key management decisions by farmers in the Sudano–Sahelian zone, where onset of rainfall is unreliable, are taken in May–June before planting. Usually, dry preseason conditions reduce yields (Yamoah et al. 2000).

Additionally, favorable preseason conditions: (1) enhance mineralization of nitrogen from crop residues resulting in a nitrogen flush at the onset of the season (Barrios et al. 1998), (2) stimulate early root development, enabling crops to withstand moisture stress in the course of the season, and (3) promote good germination and proper crop establishment that contribute to higher yields (Wilhite and Glantz 1985). Sivakumar (1988) and Shapiro et al. (1993) noted that in the Sahel the timing of the onset of rain is correlated to the length of the growing season. This information is pertinent with respect to (1) varietal choice, i.e. early, medium or late maturing varieties, and (2) the probability of positive responses to fertilizer application. It is also important to emphasize that farmers in general use photoperiodic varieties whose growth cycle is dependent on sowing date.

P fertilizer and millet yield

Organic amendments alone are inadequate to increase crop yields, but a combination of organic and inorganic fertilizers can improve efficiency (i.e. yield increase/fertilizer applied) of the latter and lead to modest yield increases (Bationo et al. 1993). Hence,

Table 2. Weather variables used in the study.

Variable	Symbol	Mean	Standard dev.	Minimum	Maximum
Standardized May–June rainfall	R_{mj}	0.14	0.98	−1.75	1.93
Standardized May–June rainfall squared	R^2_{mj}	0.98	1.31	0.006	3.73
Biological window, dry, > 5 °C	BW_1	271.88	55.99	204	255
Biological window, wet, > 5 °C	BW_2	38.22	22.02	0	63
Biological window, wet, > 8 °C	BW_3	50.44	40.72	0	110
May evapotranspiration (mm)	ET_m	198	2.72	191.4	199.8
May+June evapotranspiration (mm)	ET_{mj}	388.1	9.4	369.5	395.9
June evapotranspiration (mm)	Etju	190.1	6.9	178.1	196.1
July evapotranspiration (mm)	Etjl	183.4	11.4	163.8	191.3
August evapotranspiration (mm)	Etau	171.8	13.6	149.3	189.6

inorganic fertilizers are a prerequisite for sustained crop yields. Averaging across years, sites and rates, we found that differences among the three P sources are not significant at the 5% probability level. However, there was a significant site×source interaction. For instance, SSP improved yields by 12% and 2% relative to Kodjari and Tahoua PR, respectively at Bengou, 18% and 15% at Gobery, while at Sadoré SSP was inferior to the PRs (Table 3). We are unable to offer tangible arguments to explain the inferior performance of SSP at Sadoré in the present study. This inferior performance of SSP is contrary to what has been reported (Singh et al. 2001) for a relatively dry area like Sadoré. Singh et al. (2001) linked higher relative agronomic efficiency, defined as: [(Yield with PR)−(Yield in control)/(Yield with water-soluble P fertilizer)−(Yield in control)]×100, of PRs to low pH, high levels of organic carbon and higher rainfall. Organic carbon and pH are comparable and rainfall is the variable that differs among these three sites (Table 1). Thus, one would have expected higher yields with SSP fertilization than with PR at Sadoré.

However, response to 20 kg P_2O_5 ha^{-1} was greater at Bengou and Gobery than at Sadoré, i.e. for Kodjari PR 110% compared to 39% at Sadoré. Average millet yields of 570 kg ha^{-1} were similar at Bengou and Gobery. Evidently, without P application millet yields will remain low and are expected to even decline further over time with continuous mining of the soil, since crop residues are also exported from the fields for various domestic uses (Hafner et al. 1993; Bationo et al. 1993).

The findings of this study confirm those of numerous studies on the merits of P fertilization in the Sahelian zone (Traoré 1974; Hafner et al. 1993; Bationo et al. 1993). However, adoption of fertilizer use by farmers remains low, because of liquidity constraints and the risks associated with the erratic rainfall regime.

Simulated moisture balance

Water balance models are useful in cropping system studies, as they can help to match crops with agroecological zones in terms of moisture needs. Moisture balance characteristics of the three sites, created with NSM, are shown in Figures 1–3. The period that rainfall exceeded potential evapotranspiration was longer in Bengou than in Gobery and Sadoré. This implies that, all other things being equal, yield po-

Table 3. Millet yields (kg ha^{-1}, average of three seasons) at three sites as affected by P fertilizer rates from different sources.

Site	P fertilizer rate	P sources		
		PRK	PRT	SSP
Bengou	0	310	310	310
	20	540	670	630
	40	570	690	720
	60	720	660	720
Gobery	0	300	300	300
	20	630	590	710
	40	560	610	860
	60	690	680	710
Sadoré	0	330	330	330
	20	460	510	350
	40	420	510	420
	60	520	400	400

Analysis of variance

Source	Degree of freedom	F-value	P-value
Year (Y)	2	61.7	>0.0001
Site (T)	2	26.0	>0.0001
P Source (S)	2	1.9	0.15
P rate (R)	3	43.3	0.0001
Y×S	4	0.6	0.684
S×T	4	3.6	0.0084
T×R	6	4.2	0.0008

SSP = single super phosphate; PRT = phosphate rock of Tahoua (Niger); PRK = phosphate rock of Kodjari (Burkina Faso).

tential should be higher at Bengou (total positive moisture balance of growing season = 85.7 mm) than at Sadoré (total positive moisture balance of growing season = 19.7), as in the present study (Table 3, Figures 1 and 3). The short growing period at Sadoré suggests that early maturing varieties are suitable at that site. At Bengou, the growing period is relatively longer, hence both early and medium maturing varieties might be suitable.

Correlation of weather variables with yield

The correlation analysis was performed to identify weather-related variables closely associated with yields at the three sites (Table 4). At Bengou, all variables tested were significantly corrrelated to millet yield, except R_{mj} and ET_{ju}. At Gobery, neither of the correlations was significant and at Sadoré all the variables were significantly associated with yield, except R_{mj} and ET_{jl}. In the mid-west of the USA, we found that BW_2 and BW_3 (both indicative of cumulative number of wet days in a year) were significantly and positively correlated to maize and soybean yields, but not to sorghum yields. However, BW_1 (measuring cumulative number of dry days) was inversely correlated to maize and soybean yields, but was indifferent to sorghum. Millet, like sorghum, is generally grown in low-rainfall areas and both crops are affected by dry weather conditions to a lesser extent (Maiti and Bidinger 1981).

To reduce the number of predictor variables in the model, we used principal component analysis (Table 5). The first principal component (PRIN1) explained 63%, whereas with an additional two components (PRIN2+PRIN3), 95% of the variance in the predictor variables was accounted for. Thus, the empirical model in Table 6 contains non-correlated variables from the first three principal components of the PCA.

The empirical model

Two key weather-related variables, R_{mj} and BW_3, feature in the model (Table 6). Phosphorus rate enters the model in quadratic form, as is normal with cereal responses to fertilizers. Interaction between soil moisture and P-rate determined whether P response is dependent on preseason moisture conditions.

The regression analysis shows (Table 7), as with

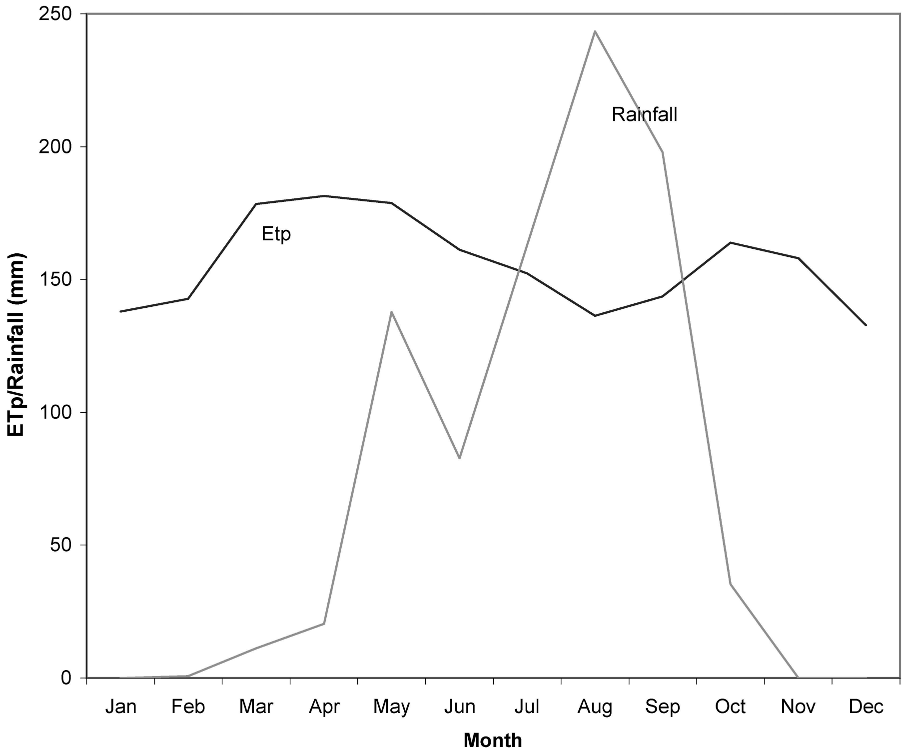

Figure 1. Moisture balance at Bengou created by the NSM.

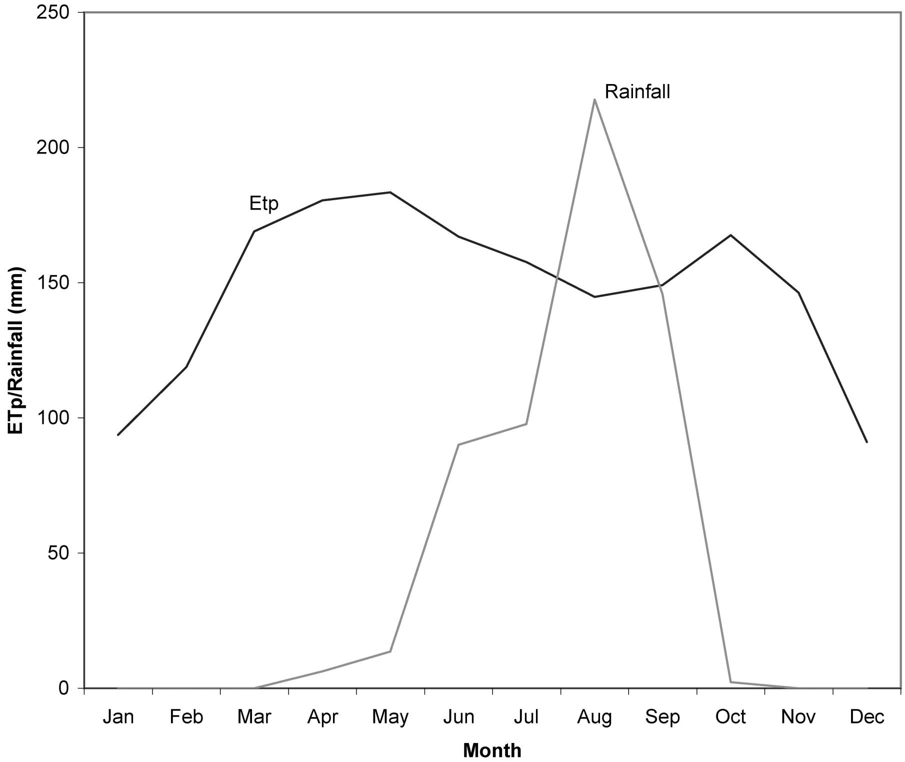

Figure 2. Moisture balance at Gobery created by the NSM.

the ANOVA, a significant and positive correlation between phosphorus application and yield, although as expected, this effect diminishes as more P is applied. A significant ($P < 0.05$) residual effect of P, resulting in 3.0 kg grain per kg P_2O_5 was found after one year but not after two years. However, we do not find evidence that soil moisture significantly influences the yield response to phosphate rock ($b = 0.06$, $P = 0.75$).

The regression coefficients suggest that 33.3 kg P_2O_5 ha^{-1} was needed to realize the maximum additional millet yield of 137.7 kg ha^{-1}. However, expected yields with and without P and P-use efficiency varied per site (Table 8). P-use efficiencies are significantly different ($P < 0.0005$) among sites, with the highest value for Gobery. Weather has an impact on yields, as an extension of one day in the biological window (BW_3) increases millet yields by 3.3 kg ha^{-1}. The elasticity of response at the mean BW_3 is 0.62. Early season rainfall R_{mj}, however, appears to negatively influence yields, although given the large variability in the onset of rains in the Sahel, this correlation may be spurious. Other possible explanations could be (1) leaching of nutrients below the root zone at the time when roots are not well developed, and (2) early season rains followed by dry periods, as occurred in 1998, do not necessarily lead to good stand establishment.

The model performs only moderately well when tested with data not included in the analysis. A regression of predicted yields against observed yields for 10 observations, that were not used in estimating the coefficients, gives an R^2 measure of 0.76 (Figure 4). Two far outliers influence this result. However, estimating the model using all the data does not lead to major changes in the estimated parameters, nor in their level of significance.

Conclusions and suggested further studies

This study demonstrates the application of simulation models in P and water management research in the Sahel. The regression model explained 52% of the

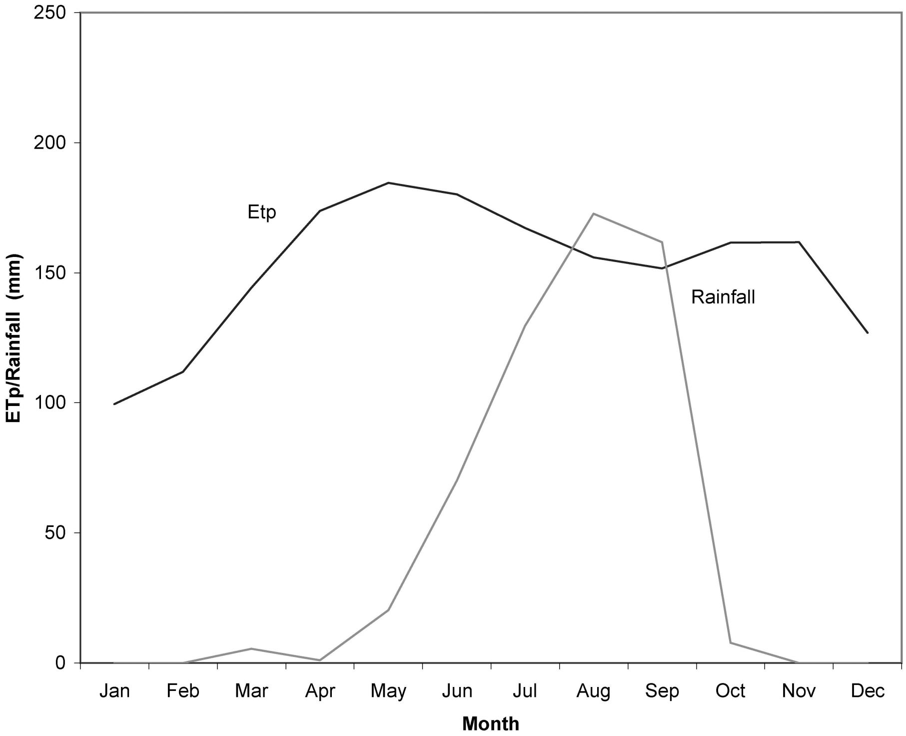

Figure 3. Moisture balance at Sadoré created by the NSM.

Table 4. Correlation coefficients (r*) between millet yield and weather variables at three sites in the Sahel.

Variable	Bengou	Gobery	Sadoré
R_{mj}	−0.23	0.07	0.08
R^2_{mj}	0.69	−0.14	0.76
BW_1	−0.68	0.19	−0.44
BW_2	−0.73	0.19	0.42
BW_3	0.71	−0.20	0.42
ET_m	0.71	0.00	0.77
ET_{mj}	0.38	−0.14	0.57
ET_{ju}	0.26	−0.14	0.35
ET_{jl}	−0.45	0.14	0.02
ET_{au}	−0.72	0.21	−0.77

r* > 0.32 is significant at the 0.05 probability level.

Table 5. Eigenvalues of predictor variables, proportion and total of variance explained by four principal components.

Principal component	Magnitude	Variance explained	Cumulative
PRIN1	5.087	0.636	0.636
PRIN2	1.451	0.181	0.817
PRIN3	1.062	0.133	0.950
PRIN4	0.325	0.041	0.991

Table 6. Summary statistics of variables in the regression model.

Variable	Description	Mean	Std. dev.
Yield	kg millet grain ha^{-1}	576.1	282.6
Gobery	1 if site is Gobery, 0 otherwise	0.31	
Sadoré	1 if site is Sadoré, 0 otherwise	0.34	
P	Rate of P_2O_5 in kg ha^{-1}	24.2	23.5
P^2	Rate of P_2O_5 squared	1134.0	1387.0
SSP	1 if SSP, 0 if rock phosphate	0.40	
P×SSP	Rate of P_2O_5 from SSP in kg ha^{-1}	8.0	17.6
P^2×SSP	Rate of P_2O_5 from SSP squared	371.8	946.9
BW_3	Number of days that soil moisture is above the permanent wilting point (wet days)	106.4	46.96
P×BW_3	Interaction of P rate and number of days (P*BW_3)	2270.0	2742.0
R_{mj}	Standardized index of rainfall in May and June	−0.17	0.47
P_{t-1}	Rate of P_2O_5 in kg ha^{-1} in previous year	30.0	22.4
P_{t-2}	Rate of P_2O_5 in kg ha^{-1} two years previous	24.1	23.3

Table 7. Results of multiple regression analysis.

Variable	Coefficient	t-statistic	P value
Constant	−37.35	0.341	0.734
Gobery	157.2	3.060	0.003
Sadoré	−112.8	2.287	0.024
P	8.262	1.977	0.050
P^2	−0.124	2.389	0.018
P×SSP	4.238	1.013	0.313
P^2×SSP	−0.057	0.715	0.476
BW_3	3.349	4.254	<0.0001
R_{mj}	−295.2	6.309	<0.0001
P×BW_3	−0.057	0.324	0.746
P_{t-1}	3.010	2.023	0.045
P_{t-2}	1.855	1.420	0.158
No. of observations	170		
R^2	0.5174		

Table 8. Yields and P-efficiency.

Site	Yield without P_2O_5 (kg grain ha^{-1})	Yield with 33.3 kg P_2O_5 ha^{-1}	P efficiency* (kg ha^{-1})/(kg ha^{-1})
Bengou	433.9	571.6	17.1
Gobery	612.5	750.2	22.5
Sadoré	244.1	381.8	11.5

*Significantly different at $P < 0.0005$ among sites.

variability in millet yields using two key composite weather variables. Despite the short duration of the study, we were able to quantify the effect of P, residual P and soil moisture on millet yields, supporting the conclusions from previous research identifying P and moisture deficiency as the most critical factors in the Sahel (Bationo and Ntare 2000; Payne 1990; Sivakumar 1990). Application of NSM in calculating the biological window at given sites is cost-effective in terms of time, human and financial resources. On-station trials controlled for management practices that vary on-farm (variety, tillage, weed control, etc.) and on-farm studies should be conducted to evaluate potential effects of P deficiency. Such studies could test the following hypotheses: (1) under normal conditions, crop productivity will be higher in areas with higher total positive moisture balances during the growing season, and (2) areas with larger biological windows are likely to have higher partial factor productivity of fertilizer.

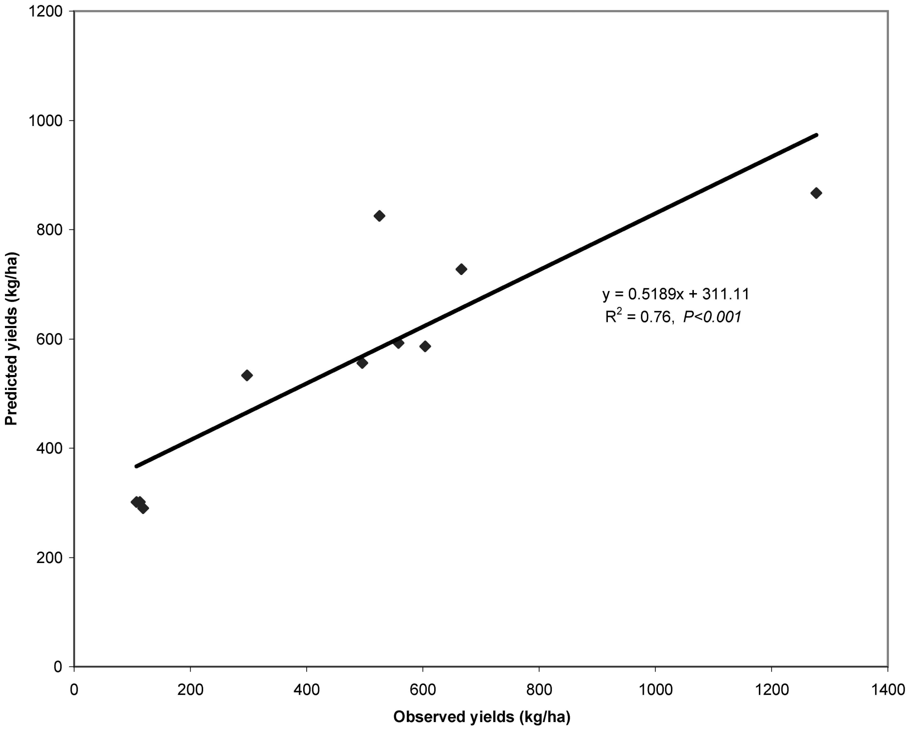

Figure 4. Observed versus predicted yields by the regression model.

References

Barrios E., Kwesiga F., Buresh R.J., Sprent J.I. and Coe R. 1998. Relating preseason soil nitrogen to maize yield in tree legume-maize rotations. Soil. Sci. Soc. Am. J. 62: 1604–1609.

Bationo A. and Ntare B.R. 2000. Rotation and nitrogen fertilizer effects on pearl millet, cowpea and groundnut yield and soil chemical properties in sandy soil in the semi-arid tropics, West Africa. J. Agricult. Sci. Cambridge 134: 277–284.

Bationo A., Henao J. and Anand Kumar K. 1999. Phosphorus use efficiency as related to sources of P fertilizers, rainfall, soil and crop management in the West African Semi-arid Tropics. In: Adu-Gyamfi J.J. (ed.), Food Security in Nutrient-stressed Environments: Exploiting Plants Genetic Capabilities. ICRISAT, Pantancheru, India.

Bationo A., Christianson C.B. and Klaij M.C. 1993. The effect of crop residue and fertilizer use on pearl millet yields in Niger. Fert. Res. 34: 251–258.

Cady F.B. 1991. Extrapolation of experimental results from a series of on-farm trials. In: Mutsaers H.J.W. and Walker P. (eds), On-Farm Research in Theory and Practice. IITA, Ibadan, Nigeria, pp. 95–101.

Christianson C.B., Bationo A. and Baethgen W.E. 1990. The effect of soil tillage and fertilizer use on pearl millet yields in Niger. Plant Soil 123: 51–58.

De Ridder N. and Van Keulen H. 1990. Some aspects of the role of organic matter in sustainable intensified arable farming systems in the West African semiarid tropics (SAT). Fert. Res. 26: 299–310.

Draper N.R. and Smith H. 1966. Applied Regression Analysis. John Wiley and Sons, New York.

FAO 1993. Crop Production Yearbook No. 46. FAO, Rome, Italy.

Hafner H., George E., Bationo A. and Marschner H. 1993. Effect of crop residue on root growth and phosphorus acquisition of pearl millet in an acid sandy soil in Niger. Plant Soil 150: 117–127.

Maiti R.K. and Bidinger F.R. 1981. Growth and development of the pearl millet plant. Research Bulletin No. 6. ICRISAT, Pantancheru, India, 14 pp.

McKee T.B., Doeskin N.J. and Kleist J. 1993. The relationship of drought frequency and duration to time scales. Proceedings 8th Conference on Applied Climatology, 17–22 January, Anaheim, California., pp. 179–184.

Payne W.A. 1990. Growth and transpirational water use efficiency of pearl millet in response to water and phosphorus supply, Ph.D. Thesis, Texas A&M University, College Station, Texas.

Quinones M.A., Borlaug N.E. and Dowswell C.R. 1997. A fertilizer-based green revolution for Africa. In: Buresh R., Sanchez P.A. and Calhoun F. (eds), Replenishing Soil Fertility in Africa. SSSA Special Publication no. 51. American Society of Agronomy and Soil Science Society of America, Madison, WI, pp. 81–95.

Shapiro B.I., Sanders J.H., Reddy K.C. and Baker T.G. 1993. Evaluating and adapting new technologies in a high-risk agricultural system – Niger. Agricult. Syst. 42: 153–171.

Singh U., Wilkens P.W., Henao J., Chein S.H., Hellums D.T. and Hammond L.L. 2001. An expert system for estimating agronomic effectiveness of freshly applied phosphate rock. Presented as a seminar paper at IFDC-Africa, Lome Togo. 20 pp.

SAS 1998. StatView reference. 2nd edn. SAS Institute Inc., Cary, North Carolina.
Sivakumar M.V.K. 1990. Exploiting rainy season potential from the onset of rains in the Sahelian zone of West Africa. Agricult. Forest Meteorol. 51: 321–332.
Sivakumar M.V.K. 1988. Predicting rainy season potential from the onset of rains in southern Sahelian and Sudanian climatic zones of West Africa. Agricult. Forest Meteorol. 42: 295–305.
Traoré M.F. 1974. Etude de la fumure minérale azotée intensive des céréales et du rôle spécifique de la matière organique dans la fertilité des sols au Mali. Agron. Trop. 29: 567–586.
Van Wambeke A., Hastings P. and Tolomeo M. 1992. Newhall simulation model – A BASIC program for the IBM PC (DOS 2.0 or later). Department of Agronomy, Cornell University, Ithaca, New York.
Waltman W.J., Siolkosz E.J., Mausbach M.J., Svoboda M.D., Miller D.A. and Kolb P.J. 1997. Soil climate regimes of Pennsylvania. Pennsylvania State Univ. Agric. Exp. Station Bull. no. 873.
Wilhite D.A. and Glantz M.H. 1985. Understanding the drought phenomenon: the role of definitions. Water Int. 10: 110–120.
Willmott C.J. and Wicks D.E. 1980. An empirical method for the spatial interpolation of monthly precipitation within California. Phys. Geogr. 1: 59–73.
Yamoah C.F., Walters D.T., Shapiro C.A., Francis C.A. and Hayes M. 2000. Standardized Precipitation Index and nitrogen rate effects on yields and risk distribution of maize in rainfed cropping systems. Agricult. Ecosyst. Environ. 80: 113–120.