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Use of the APSIM model in long term simulation to support decision making regarding nitrogen management for pearl millet in the Sahel

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ABSTRACT

Soil fertility and climate risks are hampering crop production in the Sahelian region. Because experiments with only a few fertility management options on a limited number of sites and years cannot fully capture the complex and highly non-linear soil–climate–crop interactions, crop growth simulation models may suitably complement experimental research to support decision making regarding soil fertility and water management. By means of a long term (23 years) scenario analysis using the Agricultural Production Systems Simulator (APSIM) model, this study investigates millet response to N in view of establishing N recommendations better adapted to subsistence small-holder millet farming in the Sahel. Prior to this, the APSIM model was tested on a rainfed randomized complete block experiment carried out during the 1994 and 1995 cropping seasons, having contrasting rainfall conditions. The experiment combined, at three levels each, the application of cattle manure (300, 900 and 2700 kg ha^{-1}), millet residue (300, 900 and 2700 kg ha^{-1}) and mineral fertilizer (unfertilized control, 15 kg N ha^{-1} + 4.4 kg P ha^{-1} and 45 kg N ha^{-1} + 13.1 kg P ha^{-1}) at ICRISAT Sahelian Center, Niger. The model suitably predicted plant available water PAW and the simulated water and nitrogen stress were in agreement with measurement (water) and expectation (N) regarding the fertilizer and rainfall conditions of the experiment. APSIM simulations were in satisfactory agreement with the observed crop growth except for the highest crop residue application rates (>900 kg ha^{-1}). For biomass and grain yield, the model performance was relatively good in 1994 but biomass yields were slightly overpredicted in 1995. The model was able to adequately reproduce the average trend of millet grain yield response to N inputs from manure and fertilizer, and to predict the overall observed higher grain yield in 1995 compared to 1994, despite the better rainfall in 1994. The 23-year, long term scenario analysis combining different application rates of cattle manure, millet residue and mineral fertilizer, showed that moderate N application (15 kg N ha^{-1}) improves both the long term average and the minimum yearly guaranteed yield without increasing inter-annual variability compared to no N input. Although it does imply a lower average yield than at 30 kg N ha^{-1}, the application of 15 kg N ha^{-1} appears more appropriate for small-holder, subsistence farmers than the usual 30 kg N ha^{-1} recommendation as it guarantees higher minimum yield in worst years, thereby reducing their vulnerability.

1. Introduction

In the 500–600 mm rainfall area of the Sahelian zone, it has been recognized that rainfed crop productivity is more strongly dependent on, and constrained by the low native soil fertility than by rainfall (Fussell et al., 1987; Manu et al., 1991; Bationo and Mokwunye, 1991a). Consequently, much research has been undertaken during the last 30 years in the Sahel in view of improving crop productivity by focusing on the three main fertility management strategies in the Sahel: cattle manure, millet residue and mineral fertilizer (Bationo and Mokwunye, 1991a,b; Geiger et al., 1992; Hafner et al., 1993; Bationo et al., 1995; Buerkert and Hiernaux, 1998).

As far as nitrogen management is concerned, the present-day optimal N application recommendation for rainfed millet cropping in the Nigerien Sahel has been reported as being around 30 kg N ha^{-1} (Christianson et al., 1990; Bationo et al., 1992). This recommendation is based solely on the results of field experiments

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over a limited number of years. However, it is well known that millet response to N is strongly dependent on climatic conditions, mostly the amount and temporal distribution of rainfall (Christianson et al., 1990; Sivakumar and Salaam, 1999). Hence, single-value N application recommendations are not well adapted to Sahelian conditions where temporal rainfall variability is very high. Christianson et al. (1990) reported empirical millet grain and stover yield response curves to mineral N as determined by mid-season rainfall amount. Although they provide some explanatory value, these relationships have little practical value as mid-season rainfall cannot be predicted beforehand. In addition, Akponikpe et al. (2008) have shown that these relationships do not necessarily hold for other years, experimental conditions and organic sources of N.

There is ample evidence in the literature that the 30 kg N ha^{-1} fertilizer recommendation presents a high economic risk for small-holder farmers because of the climatic constraints, besides the fact that farmers can often not afford to buy such amounts (Shapiro and Sanders, 1998; Abdoulaye and Lowenberg-Deboer, 2000; Abdoulaye and Sanders, 2005). In addition, rather than seeking to maximize yields, subsistence millet farming generally aims at minimizing inter-annual yield variability while trying to guarantee some minimal yield needed to cover the food requirements (Fussell et al., 1987; Brouwer et al., 1993). Current N recommendations have clearly not been derived based on such considerations. Various approaches can be investigated to arrive at more appropriate recommendations: testing different sources of N to enhance N use efficiency (Christianson et al., 1990; Bationo and Mokwunye, 1991a,b; Bationo et al., 1992), testing different N management strategies, including hill-placed fertilizer application (Fatondji et al., 2006; Tabo et al., 2007), site-specific fertility management (Brouwer and Powell, 1998; Gandah et al., 2003a,b), intercropping and rotation with legumes (Klaij and Ntare, 1995; Bagayoko et al., 2000; Bationo and Ntare, 2000) but also long term fertilizer response experiments. This latter approach is, however, extremely costly and such experiments are extremely rare in the Sahelian region. To overcome this limitation, short term experiments can usefully be complemented with properly validated mathematical dynamic crop models which simulate the most important biophysical processes (soil water and N dynamics and crop growth).

So far studies involving dynamic models applicable to low input millet-based systems in the Sahel are scarce and published results mostly emphasize only the millet water balance. Bley et al. (1991) used the SWATRER model to establish a risk-probability map for rainfall-limited millet production in southwest Niger. Later on, Fechter et al. (1991) and Fechter (1993) evaluated the SWATRER and CERES-millet models for predicting water balance and yield. Thornton et al. (1997) also used CERES-millet for early warning in Burkina-Faso and Soler et al. (2008) used it for determining the optimum millet planting dates. SARRAH, a crop model simulating attainable yield under optimal soil fertility conditions was used to analyze the impact of regional climatic variability on millet yield (Sultan et al., 2005) and to predict agricultural plot yield based on Global Circulation Model output (Baron et al., 2005).

The Agricultural Production Systems Simulator APSIM (Keating et al., 2003) is one of the few available dynamic crop growth simulation models capable of dealing with water and N dynamics under different fertility management conditions (mineral and organic amendments). It has recently been complemented with a specific millet tillering growth module (Van Oosterom et al., 2002) that recognizes tillers as functional entities in millet cropping systems (Van Oosterom et al., 2001a,b, 2002). The APSIM millet growth module was originally parameterized based on data from on-station experiments in India (ICRISAT Patancheru), under optimum growing conditions, covering a range of plant densities, photoperiods and Indian genotypes (Van Oosterom et al., 2001b, 2002). The model could adequately predict biomass, grain yield, and leaf area index (LAI). For these reasons, APSIM currently appears to be the best suited model for simulating millet response to climate and soil fertility management. However, a necessary prerequisite is to evaluate the performance of the model through a proper calibration and validation for Sahelian millet cultivar(s) and agro-climatic conditions. The main objectives of this study are therefore to (1) test the performance (calibration and validation) of the APSIM model in terms of millet response, under Sahelian climatic conditions, to the three main fertility management practices: manure, crop residue and fertilizer and (2) to use the validated model to identify N application rates that are better adapted to subsistence small-holder millet farming in the Sahel. The latter is achieved through scenario analyses based on long term (23 years) simulations.

2. Materials and methods

2.1. Experimental data

This research capitalizes on 2 past (experiments I and III) and one recent (experiment II) on-station field experiment. All the experiments took place during the normal millet cropping season at Sadoré, Niger (13°15′N, 2°17′E and altitude of 240 m) on the experimental farm of the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) Sahelian Centre, located 45 km south-east of Niamey, the capital city of Niger.

Experiment I was conducted during the 1994 and 1995 rainy seasons at Sadoré. It aimed at evaluating the effect of combined application of cattle manure, millet residues and mineral fertilizer on pearl millet production. Details of this experiment have been published elsewhere (Akponikpe et al., 2008). Data from this experiment was used for model validation (see Section 2.3). The experimental design consisted of a fully factorial randomized block experiment with 3 factors at 3 levels each: (1) uniformly broadcast millet residue application (300, 900 and 2700 kg ha^{-1}, noted as R1, R2 and R3, respectively), (2) uniformly broadcast cattle manure application (300, 900 and 2700 kg ha^{-1}, noted as M1, M2 and M3, respectively), and (3) hill-placed nitrogen (as calcium ammonium nitrate) and broadcast phosphorus (as single super phosphate) mineral fertilizer application (0 N + 0 P, 15 kg ha^{-1} N + 4.4 kg ha^{-1} P and 45 kg ha^{-1} N + 13.1 kg ha^{-1} P, noted as F1, F2 and F3, respectively). The millet cultivar CIVT (Composite Inter-Varietal de Tarna, early maturing, 95 days approximately) was sown in hills without prior tillage after the first sufficient rainfall event (>20 mm) in each year, at a density of 12,500 hills ha^{-1} thinned to 2 plants $hill^{-1}$ in 1994 and 10,000 hills ha^{-1} thinned to 3 plants $hill^{-1}$ in 1995. Millet was sown on 6 June 1994 and 20 June 1995 and harvested on 20–23 September 1994 and on 26–27 September 1995. Above ground biomass was measured by destructive sampling several times during the season in 1994. Plant available water (PAW) was computed from water content profile measurements made every two weeks in all plots with a field-calibrated neutron probe. Final biomass and grain yield were measured both years.

Experiment II aimed at performing a genetic characterization of the Nigerien millet cultivar CIVT because the default parameterization of the APSIM millet module, which is based on Indian cultivars, lead to completely unsatisfactory results. The data of this experiment was used to determine the value of crop specific parameters of the APSIM millet module through direct measurements or model calibration, depending on the parameter (see Section 2.3). The experiment took place in 2005 under optimum water (irrigation during dry spells) and nutrient conditions considering four sowing dates at one month interval (19 April, 19 May, 18 June and 19 July), corresponding to the maximum and reliable millet sowing period in the Sahel. Detailed crop phenology and growth were recorded and served to compute the thermal time durations between crop phases from germination to maturity. Further details regarding this experiment can be found in Akponikpe (2008).

Experiment III aimed at quantifying the soil-water balance components in the absence of any crop (no millet or other crop and regularly weeded field). Data from this experiment were used to calibrate specific parameters of the APSIM soil-water module (see Section 2.3). The experiment took place during the rainy season between 28 May 1996 and 25 October 1996. Neutron probe measurements were recorded every two weeks on 30 access tubes spaced 20 m apart on a square grid within a 80 m × 100 m field. Measurements were taken every 0.15 m between 0.15 and 2.4 m depth. Plant available water was calculated as the difference between volumetric water content and water content at soil lower limit (−15 bar pressure potential) between 0 and 1.50 m depth.

2.2. Model description and inputs

2.2.1. APSIM model overview

The Agricultural Production Systems Simulator (APSIM) is a modular modeling framework that has been developed by the Agricultural Production Systems Research Unit in Australia (Keating et al., 2003). Six modules, a specific crop module (APSIM-millet 3.6), a soil-water module (SOILWAT2), the soil nitrogen module (SOILN2), the residue module (RESIDUE2), the fertilizer module (FERTILIZ) and the manure module (MANURE) were linked within APSIM to simulate the cases described in this paper. Input data required by the APSIM model are related to the climate (daily minimum and maximum temperatures, radiation and rainfall), crop genetic and soil characteristics as well as plant and soil management (planting, organic amendment or fertilizer application).

2.2.2. Soil water module (SOILWAT2)

The soil-water module is a cascading water balance model (Probert et al., 1998; Keating et al., 2003). Water movement is described using separate algorithms for saturated or unsaturated flow (Jones et al., 2003). Redistribution of solutes, such as nitrate- and urea-N, is carried out in this module. Evaporation is described as a two-stage process (energy-limited and water limited) based on potential evaporation (Priestly-Taylor) and corrected for residue and plant cover.

2.2.3. Manure, residue and fertilizer modules

The manure, residue and fertilizer modules have similar structure in APSIM. Manure, residues and fertilizer on the surface can be removed or added, incorporated into the soil during tillage operations, or decompose on the surface. Manure, residue and fertilizer are defined in terms of their nature, mass, their inorganic and organic nitrogen contents and carbon content. Decomposition of surface residue or manure is calculated using a simple exponential decay function (Probert et al., 1998; Keating et al., 2003). A constant potential rate is specified as an input parameter, and adjusted for moisture, temperature and the C:N ratio of the manure or residue. Decomposition of residues with a high C:N ratio creates N immobilization demand, which is satisfied from mineral-N in the uppermost soil layers. In extreme situations, insufficient mineral-N availability in the soil restricts the decomposition of residues.

At present the APSIM-millet module is not P sensitive and the present study therefore focused on the millet response to N. However, many published works have shown that millet does not respond to N unless a minimal amount of P is provided, because P is the most limiting soil factor for millet production in the Nigerien Sahel region (Buerkert and Stern, 1995; Buerkert et al., 2001). In all treatments of experiment I, some P was added, mostly through fertilizer and/or manure. This addition of P was roughly proportional to the amount of N added. The P/N ratio was 20% for manure and 29% for fertilizer. One may therefore assume that for most treatments, P was not limiting and hence the use of a water and N-based crop growth simulation model remains acceptable.

2.2.4. Millet module

The millet module is specifically designed to deal with the tillering nature of the millet crop (Van Oosterom et al., 2001a,b, 2002). The module simulates, on a daily time step, the biomass (above and below ground), grain yield, leaf area development and yield components for individual tillers. Pearl millet growth responds to climate (temperature, rainfall, radiation, and photoperiod), soil water supply (SOILWAT2 module), and soil nitrogen (SOILN2 module) and returns information on soil water and soil nitrogen. There are 11 crop stages and ten phases (time between stages) in the millet module. Commencement of each stage is determined by accumulation of thermal time, except for the sowing to germination period which is driven by soil moisture (Table 1). Thermal time is calculated using 10 °C, 33 °C and 47 °C as the base, optimum and maximum temperature, with linear interpolations between these points (Ong, 1983; Van Oosterom et al., 2001b). Between the stage of emergence and flag leaf appearance, the calculated daily thermal time is reduced when water or nitrogen stresses occur, resulting in delayed phenology when the plant is under stress. The duration and timing of most crop phases are determined by genotype- and axis-specific, fixed thermal time input values.

2.3. Model parameterization and calibration

2.3.1. Soil water module (SOILWAT2)

Drained upper limit water content at field capacity (DUL), drainage rate coefficient between soil layers at water content > DUL (SWCON, considered equal for all depths), as well as the first (U) and second (CONA) stage soil evaporation coefficients were calibrated. Calibration was performed by optimization using the nonlinear parameter estimation package PEST® (Doherty, 2004). The optimization seeked to minimize the root mean square error (RMSE) between the measured and simulated values of PAW in experiment III:

$$\mathrm{RMSE} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(S_i - O_i)^2} \quad (1)$$

where S_i and O_i are the simulated and the observed values, respectively, and n is the number of observations.

The bare soil runoff curve number was set to 50 to account for the fact that runoff was very low as a result of the flat topography and the high infiltration rates which are characteristic of the sandy soil at the experimental site. Parameterization of the lower limit water content at 15 bar matric pressure (LL15), bulk density (BD), organic carbon content (OC), initial NH_4–N and NO_3–N and pH was done using published data or measurements during experiment I (Table 2).

2.3.2. Manure, residue and fertilizer modules

Millet residue and manure chemical composition needed in the model were measured and taken from experiment I. Potential decomposition rates were obtained from the literature (Table 1) (Esse et al., 2001; Fatondji, 2002).

2.3.3. Millet module

The parameterization of the targeted millet cultivar CIVT was based on experiment II. Detailed crop phenology recorded during this experiment served to compute the thermal time durations between crop phases from germination to maturity (Table 1).

Table 1
Input data required for the standard APSIM simulation model.

Parameter or variables	Acronym	Value	Units
Phenology			
Sowing: germination	–	PAW > 0.0[a]	mm mm^{-1}
Germination: emergence	–	10.7 + 1.17 × SwD[b]	°C days
Emergence: end juvenile	TT_EMERG_TO_ENDJUV	483	°C days
End-juvenile: floral initiation	–	112 × (photoperiod – 13.4)	°C days
Emergence: flag leaf	–	46 × leaf number	°C days
Flag leaf: flowering	TT_FLAG_TO_FLOWER	115	°C days
Flowering: start grain filling	TT_FLOWER_TO_START_GRAIN	112	°C days
Flowering: maturity	TT_FLOWER_TO_MATURITY	380	°C days
Maturity: harvest-ripe	TT_MATURITY_TO_RIPE	1	°C days
Genetic			
Cultivar name	Name	CIVT	
Regression of largest leaf area on leaf number	Y0_CONST	−807	mm^2
Regression of largest leaf area on leaf number	Y0_SLOPE	1137	mm^2 per leaf
Potential grain number per head	HEAD_GRAIN_NO_MAX	5250	grains head^{-1}
Potential grain growth rate	GRAIN_GTH_RATE	0.42	mg grain^{-1} day^{-1}
Radiation and water use			
Radiation use efficiency	RUE	1.2[c]	g MJ^{-1}
Transpiration use efficiency coefficient	TRANSP_EFF_CF	0.009	kPa
Millet water lower limit	LL	0.044	m^3 m^{-3}
Rate of soil water extraction	KL	0.080	–
Soil surface			
Soil albedo	SALB	0.13	–
Stage-1 soil evaporation coefficient	U	8.65	mm
Stage-2 soil evaporation coefficient	CONA	0.01	–
Bare soil runoff curve number	CN2_BARE	40	–
Reduction in CN2_BARE due to cover	CN_RED	28	–
Each soil layer[d]			
Layer drainage rate coefficient	SWCON	0.41	–
Inert fraction of organic carbon	FINERT	0.44	–
Non-inert fraction of carbon in microbial products	FBIOM	0.03	–
Soil C/N ratio	SOIL_CN	14.5	–
Time constant for N millet uptake by diffusion	NO3_DIFF_CONST	2	day
Other managements			
Residue/manure/mineral fertilizer application	Type, amount, date		
Millet residue potential decomposition rate	POT_DECOMP_RATE	0.05	day^{-1}
Cattle manure potential decomposition rate	MANURE_POT_DECOMP_RATE	0.05	day^{-1}

[a] PAW in seedling zone (0–0.03 m soil depth).
[b] Sowing depth.
[c] 1.2 before anthesis and 0.8 thereafter.
[d] Provided in Table 2 when variable.

Required leaf area parameters (regression coefficients between the area of the largest leaf and total leaf number) were also derived from this experiment (Table 1). Crop N nutrition, the crop water uptake parameters (millet lower limit LL and rate of water extraction KL), and radiation use efficiency (RUE) were the default values of the model. Using measured and simulated grain yields for selected treatments of experiment I, parameter optimization with PEST of LL, KL, RUE, the transpiration efficiency coefficient, the grain growth rate, and the maximum number of grains per head did not result in significantly better simulation results than those obtained

Table 2
Soil physical and chemical model inputs for the experimental field at ICRISAT Sahelian center. LL = lower limit (water content at −15 bar pressure potential), DUL = drained upper limit, SAT = saturated volumetric water content, BD = bulk density, OC = organic carbon.

Layer (m)	LL[a] (m^3 m^{-3})	DUL[b] (m^3 m^{-3})	SAT[c] (m^3 m^{-3})	BD[a] (Mg m^{-3})	OC[d] (%)	NH4–N[a] (mg kg^{-1})	NO_3–N[a] (mg kg^{-1})	pH_{H2O}[d]
0–0.05	0.02	0.07	0.33	1.65	0.19	0.50	6.00	5.40
0.05–0.1	0.03	0.07	0.37	1.55	0.19	0.50	6.00	5.60
0.1–0.2	0.03	0.07	0.37	1.54	0.19	0.50	6.00	5.60
0.2–0.3	0.03	0.07	0.39	1.48	0.13	0.50	6.00	5.70
0.3–0.4	0.04	0.07	0.35	1.59	0.13	0.10	0.10	5.30
0.4–0.5	0.04	0.07	0.35	1.59	0.10	0.10	0.10	5.00
0.5–0.7	0.04	0.07	0.35	1.58	0.09	0.10	0.10	5.20
0.7–1.0	0.04	0.07	0.34	1.62	0.08	0.10	0.10	5.20
1.0–2.0	0.04	0.07	0.34	1.61	0.08	0.10	0.10	5.20

[a] From Fechter (1993).
[b] Calibrated with PEST®.
[c] Calculated as SAT = 1 − (BD/2.65) − 0.05.
[d] From experiment I.

using default parameter values. Default parameters were therefore retained.

2.4. Model evaluation

Model evaluation was performed on the 27 treatments and the two years of data of experiment I with respect to PAW (1994–1995), temporal above ground biomass (1994) and final biomass and grain yield (1994–1995). Given that none of the model parameters had been calibrated on the basis of experiment I, the model performance evaluation can be considered as a true validation.

Measured and simulated data were compared graphically and analyzed statistically (Loague and Green, 1991; Willmott et al., 1985). The statistical criteria are based on the analysis of residual errors, i.e., the difference between observed and simulated values. We computed the RMSE (Eq. (1)) and the d index of agreement (Willmott et al., 1985), $0 \le d \le 1$

$$d = 1 - \left[\frac{\sum_{i=1}^{n} (S_i - O_i)^2}{\sum_{i=1}^{n} \left(|S_i - \bar{O}| + |O_i - \bar{O}| \right)^2} \right] \qquad (2)$$

where $\bar{O}$ is the mean of the observed values. One would expect to have, for good model performance, values of RMSE and d as close as possible to 0 and 1, respectively. High values of RMSE or d values close to 0 indicate poor model performance. RMSE and d were computed for individual treatments for the biomass and PAW throughout the growing period whereas they were calculated for the combined treatments for final biomass and grain yield.

2.5. Model application: long term computer simulation

The calibrated and validated APSIM model was used to simulate a 6 × 6 × 2 factorial scenario analysis combining manure at 6 levels (0–2500 kg ha^{-1} with 500 kg ha^{-1} increments), N fertilizer as CAN at 6 levels (0–50 kg N ha^{-1} with 10 kg N ha^{-1} increments) and millet residue at 2 levels (0 and 500 kg ha^{-1}) over a period of 23 years (1983–2005) using daily agro-climatic data (rainfall, minimum and maximum temperature and solar radiation) from the ICRISAT research station at Sadoré. Crop residue application rates >500 kg ha^{-1} were not simulated as model response to such levels of residue proved not to be suitable (see Section 3). The N content of the manure was set at 1.0%, corresponding to the mean measured N content of the manure added during experiment I. Rainfall characteristics of the simulation period are presented in Fig. 1. Sowing and resowing of millet were parameterised to mimic farmer practices in the area. During each simulation year, millet sowing was allowed when a total rainfall over 15 mm occurred over three consecutive days between May 1 and June 30. Only 10 mm was required to initiate sowing between 1 and 30 July if no sowing was possible previously or if the crop sown previously failed due to severe drought. Crop permanent wilting, possibly leading to resowing, was reached when the simulated crop water deficit factor dropped under 0.5 for 15 consecutive days. However, no sowing or resowing was allowed after July 30 because after this date the remaining growing season would inevitably be too short. Plant density was set to 30,000 plants ha^{-1}. All the manure or residue was applied on May 1st every year. For N fertilizer, the application rate was split into 2: the first (0–30 kg N ha^{-1}) on the 1st day after sowing (DAS) and the remaining at 50 DAS. In case of resowing, no additional fertilizer was applied.

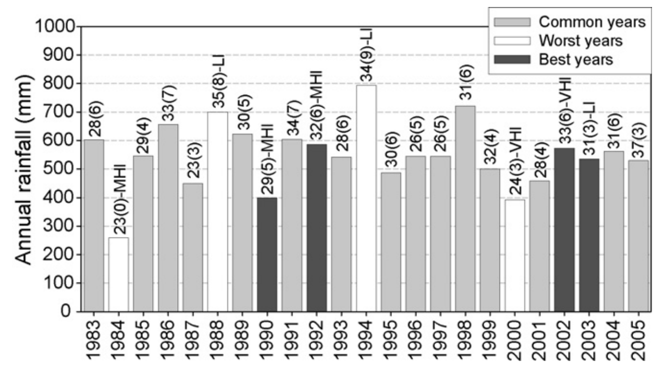

Fig. 1. Annual rainfall, number of rainfall events (top labels) with number of heavy rains exceeding 30 mm, in brackets, and year performance identification by APSIM from millet yield simulation at ICRISAT Sahelian center, Niger from 1983 to 2005. LI, MHI, VHI respectively denote low, medium to high, and very high N input under which a given year was identified as worst or best in terms of grain yield.

3. Results

3.1. Rainfall, temperature and solar radiation during experiment I

Rainfall during the cropping periods of experiment I was 721 mm in 1994 and 431 mm in 1995, whereas for the whole year it was 794 and 486 mm, respectively (Fig. 2a). The latter correspond, respectively, to 146 and 89% of the long term annual average rainfall in Sadoré. Minimum daily temperature ranged between 20 and 28 °C with an average of 23 °C, and maximum daily temperature ranged between 26 and 39 °C with an average of 34 °C during the two years. Average daily solar radiation was 22 MJ m^{-2} and was comprised between 6 and 27 MJ m^{-2}. Although temperature and radiation were similar during the two years, the contrasting rainfall conditions make these two years very relevant for testing the model in terms of millet response to fertility management options in the Sahel.

3.2. Simulation of soil water dynamics

On the basis of the data from experiment III, the best calibration was obtained with the following set of parameters: SWCON (0.41), CONA (0.01 mm), DUL (0.07 m^3 m^{-3}) and U (8.65 mm). RMSE and d statistics were 9 mm and 0.96, respectively, for PAW (not shown). Simulated PAW matched well with observations during the entire calibration experiment.

Using the calibrated values of the above-mentioned parameters, the APSIM model was run for the experimental conditions of experiment I. The range of RMSE values for PAW was 19–27 mm in 1994 and 12–27 mm in 1995 across the 27 treatments, which corresponds to a mean error in volumetric water content of 0.8–1.8% over the entire rooting depth (0–1.50 m) (Fig. 3a). The index of agreement d, calculated for each individual treatment, ranged from 0.77 to 0.89 in 1994 and from 0.51 to 0.84 in 1995 (Fig. 3b). Model performance was satisfactory in simulating PAW (Fig. 4a–d).

3.3. Millet growth and yield evaluation (experiment I)

Simulations showed that no treatment suffered from water deficit in 1994 whereas two short water stress periods were simulated around 50 and 90 DAS for high fertilized treatments in 1995 (Fig. 2). The lowest fertilized treatment R1F1M1 faced, according to simulation, a long severe nitrogen stress between 50 and 100 DAS each year. The highest fertilized treatment was not affected by nitrogen stress in 1995 but two moderate N stress periods were simulated around 20 and 80 DAS in 1994.

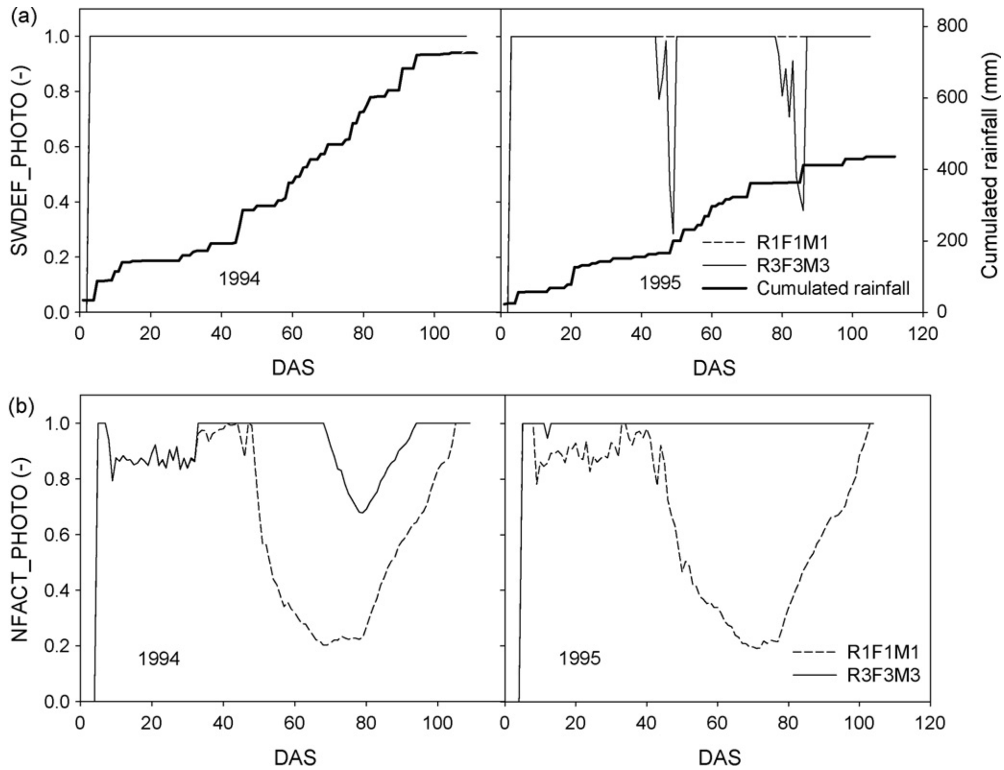

Fig. 2. Cumulative rainfall and simulated soil water deficit factor for photosynthesis (SWDEF_PHOTO) and nitrogen deficit factor (NFACT_PHOTO) for selected treatments in experiment I combining application of cattle manure, crop residue and mineral fertilizer in 1994 and 1995 at ICRISAT Sahelian center, Niger.

The evolution of measured total above ground biomass during the 1994 growing season was used to assess the simulated millet growth. RMSE ranged from 144 to 1568 kg ha^{-1} for the 27 treatments. 80% of RMSE values were below 600 kg ha^{-1} (Fig. 3a). The d index of agreement, computed for each individual treatment, ranged from 0.77 to 1.0 (Fig. 3b). APSIM simulations were in satisfactory agreement with the observed millet growth (Fig. 5a). Nevertheless high observed biomass values tended to be underestimated by the model (Fig. 5a and b). It can be noticed from Fig. 5a that these values pertained to treatments involving 2700 kg ha^{-1} crop residue (R3). Removing data of all treatments involving R3 substantially improved the model performance (Fig. 5a).

Regarding final biomass and grain yield, model performance differed between the two years of experiment I. For total above ground biomass at harvest, the RMSE was 615 and 1294 kg ha^{-1} in 1994 and 1995, respectively. The d index of agreement was 0.84 and 0.67 for these two years, respectively (Table 3). APSIM model performance was relatively good in 1994 but biomass yield was slightly overpredicted in 1995 (Fig. 6a).

The APSIM model performed also well in terms of grain yield response to fertilizer, manure and crop residue application (Fig. 6b). The RMSE was 206 kg ha^{-1} in 1994 and 1995. The d statistic was 0.73 and 0.81 for the same two years, respectively (Table 3). Experimental, within-treatment standard deviations for both total biomass and grain yield were large, which is a well known characteristic of the Sahelian environment, even for on-station experiments. Model performance could be considered satisfactory because most of the simulation results are within one standard

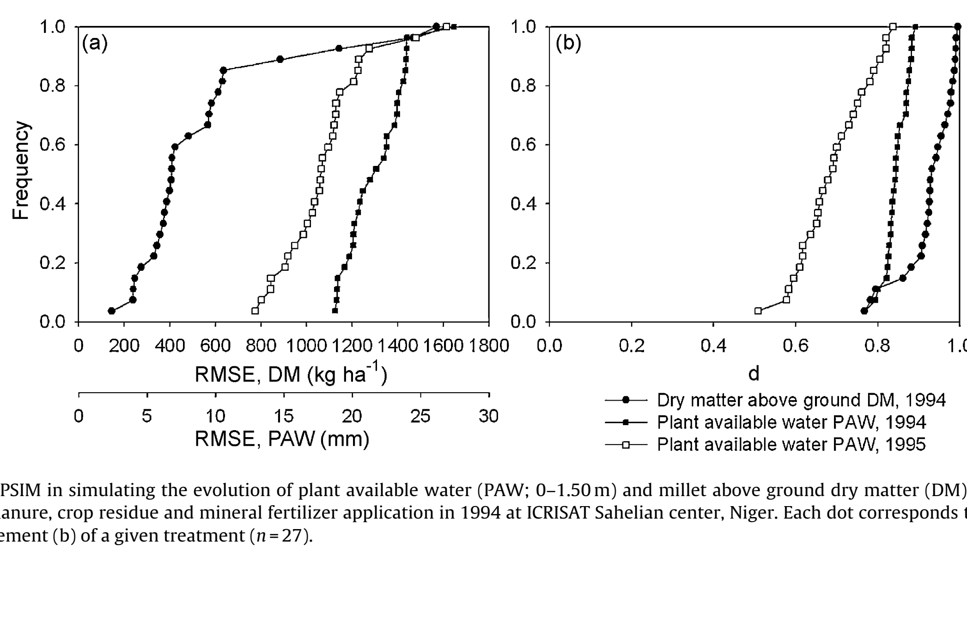

Fig. 3. Performance of APSIM in simulating the evolution of plant available water (PAW; 0–1.50 m) and millet above ground dry matter (DM) in experiment I for the 27 combinations of cattle manure, crop residue and mineral fertilizer application in 1994 at ICRISAT Sahelian center, Niger. Each dot corresponds to the seasonal RMSE (a) or Willmott d index of agreement (b) of a given treatment (n = 27).

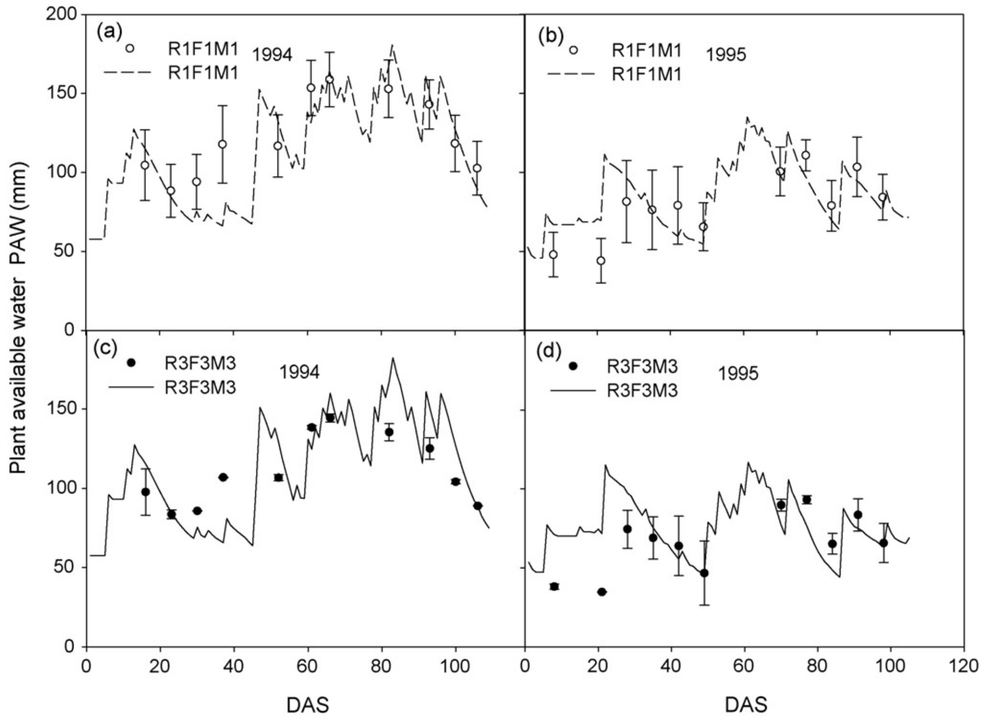

Fig. 4. Observed and APSIM simulated plant available water (PAW; 0–1.50 m) for selected treatments with combined applications of cattle manure (M), crop residue (R) and mineral fertilizer (F) in 1994 and 1995 at ICRISAT Sahelian center, Niger (experiment I). Dots and lines are, respectively, observed and simulated values. Error bars denote standard deviation of measurements (*n* = 3).

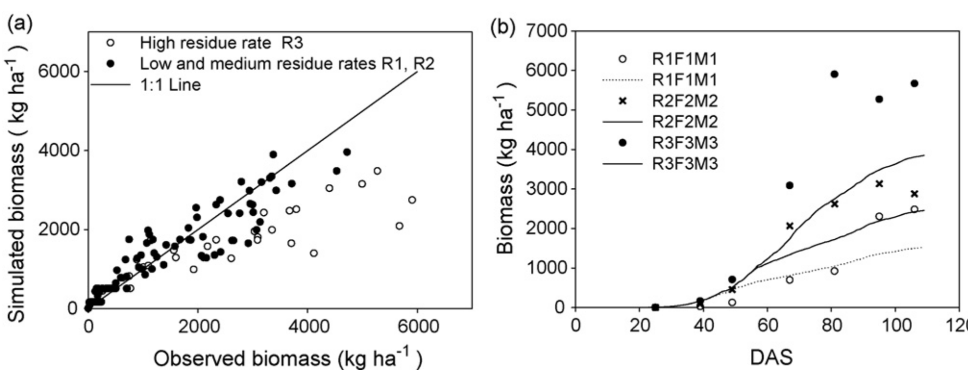

Fig. 5. Comparison between observed and APSIM simulated millet temporal above ground biomass for (a) all 27 treatments (7 dates per treatment; experiment I), and (b) three selected treatments with combined applications of cattle manure (M), crop residue (R) and mineral fertilizer (F) in 1994 at ICRISAT Sahelian center, Niger. Dots and lines are respectively observed and simulated values. R1, R2 and R3 correspond to application rates of 300, 900 and 2700 kg ha^{-1} of crop residue, respectively.

deviation of the observed values (Fig. 6). In the same way the R3 treatments were found to depreciate the performance of the model in simulating the time course of biomass, the performance in terms of biomass and grain yield was generally improved by removing these treatments (Table 3).

The model reproduced well the trend of millet grain yield response to N inputs (Fig. 7). It was able to adequately reproduce the overall higher observed grain yield in 1995 compared to 1994.

3.4. Long term N input scenario analysis

Based on the long term simulation, stover and grain yields have a similar response to organic amendments and fertilizer inputs. Maximum and long term average grain yields increase parabolically in response to N input rates (Fig. 8). Low N inputs (0–15 kg ha^{-1} N from manure and/or fertilizer) result in the lowest inter-annual variation in grain yield. At 15 kg ha^{-1} N, the long term average grain yield is

Table 3
Root mean square error (RMSE) and Willmott *d* index of agreement of simulated vs. measured millet biomass and grain yield as affected by combined application of cattle manure, crop residue and mineral fertilizer in 1994 and 1995 at ICRISAT Sahelian center, Niger (27 treatments). Values in brackets are calculated after discarding all treatments involving 2700 kg residue ha^{-1} (R3).

	Biomass yield		Grain yield	
	1994	1995	1994	1995
RMSE (kg ha^{-1})	615 (600)	1294 (1435)	206 (190)	206 (168)
d	0.84 (0.85)	0.67 (0.60)	0.73 (0.76)	0.81 (0.84)

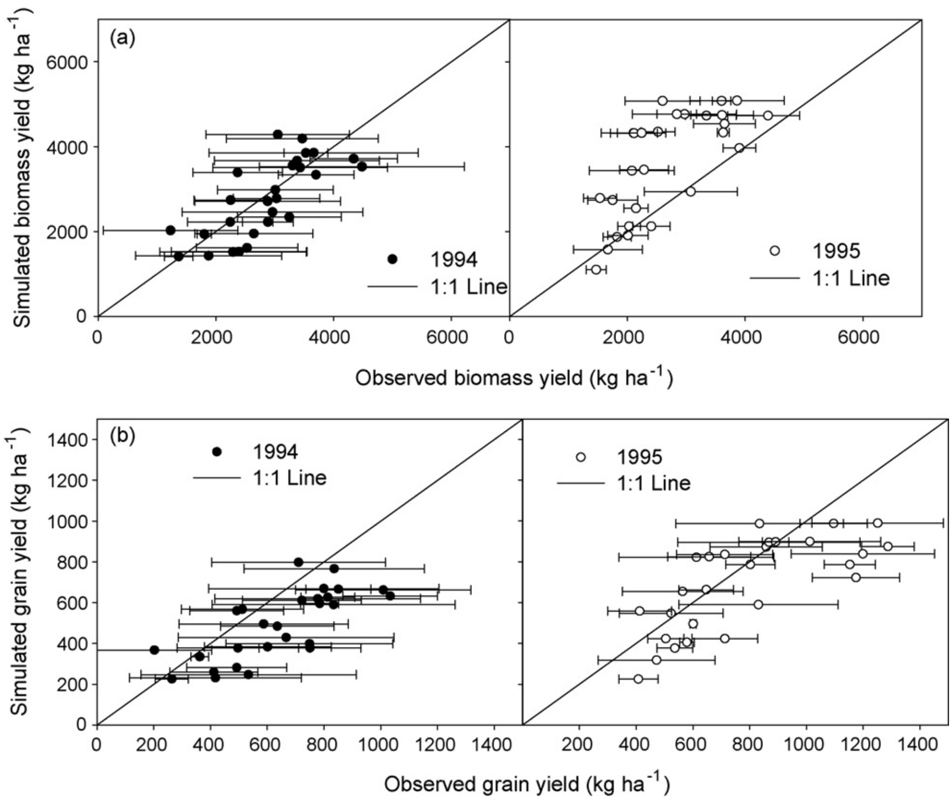

Fig. 6. Comparison between observed and APSIM simulated millet biomass (a) and grain (b) yield as affected by combined application of cattle manure, crop residue and mineral fertilizer in 1994 and 1995 at ICRISAT Sahelian center, Niger. Error bars denote standard deviation of observed means, $n = 3$.

605 kg ha^{-1} (+38% compared to 0 N) and the minimum grain yield is improved from 234 to 402 kg ha^{-1} compared to no N input. Hence, providing 15 kg ha^{-1} N guarantees at least 402 kg ha^{-1} every year while maximum grain yield reaches 742 kg ha^{-1}. For N application rates comprised between 15 and 55 kg ha^{-1} N from manure and fertilizer the long term average grain yield continues to rise (up to 780 kg ha^{-1}). However, this goes together with a higher inter-annual yield variability and a slight decrease in minimum grain yield which is rather constant around 333 kg ha^{-1}. At very high N input rates (>55 kg ha^{-1} N from manure and fertilizer), the increase in the long term average grain yield is rather low whereas the minimum yield decreases rapidly from 330 to 167 kg ha^{-1} and the inter-annual variability becomes very high.

The worst years (i.e., years with the lowest grain yield based on the long term simulation) were identified as 1988 and 1994 under low N input, 1984 under medium to high N input and 2000 under very high N input conditions (Fig. 1). 1984 and 2000 were characterized by low harvest indexes (grain/total biomass ratio between 0.08 and 0.15). Best years (i.e., years with the highest simulated grain yield) were identified as 1990 and 1992 for medium to high N input, 2002 for very high N input and 2003 for low N input (Fig. 1).

4. Discussion

4.1. Relevance of experiment I for model testing in the Nigerien Sahel

For model performance evaluation, it is essential to have a suitable control treatment, which allows to simulate the baseline soil water and N dynamics and subsequently the response to residue, manure and fertilizer applications. Traditionally, such a control

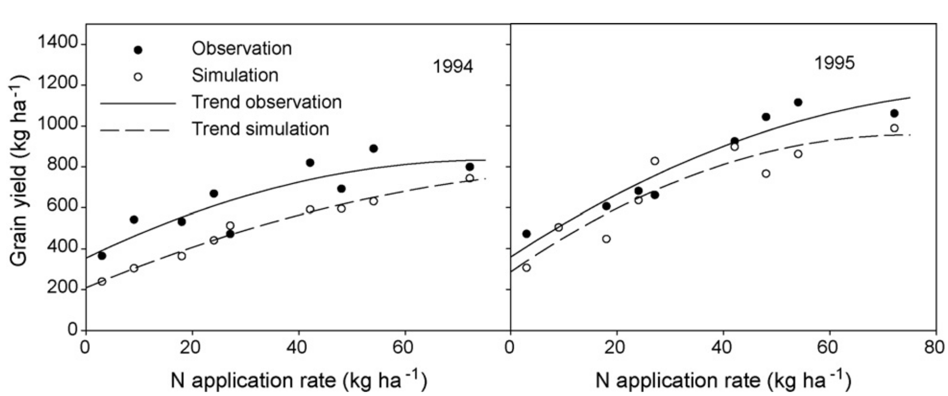

Fig. 7. Observed and simulated millet grain yield response to N inputs from combined application of cattle manure and mineral fertilizer in 1994 and 1995 at ICRISAT Sahelian center, Niger. Measured yields are averaged over all residue application rates. Trendlines are second order polynomials.

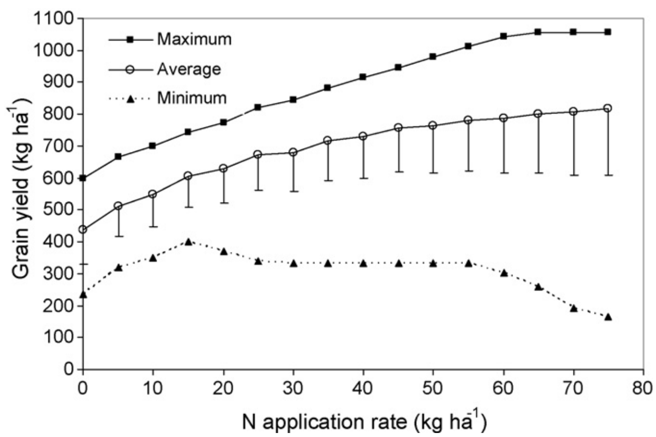

Fig. 8. Statistical parameters of 23 year (1983–2005) of simulated millet grain yield in response to N inputs from combined application of cattle manure and mineral fertilizer at ICRISAT Sahelian center, Niger. No residue was considered during simulation. Error bars denote standard deviation ($n = 23$).

treatment is viewed as being a zero-nutrient input treatment. In experiment I, no such zero-input control treatment exists as all treatments are combinations of residue, manure and fertilizer. This may appear at first as a limitation of the dataset. However, experimental results from zero-input treatments on sandy Sahelian soils invariably highlight rapid soil acidification and severe nutrient deficiencies (e.g., Buerkert and Lamers, 1999; Bielders et al., 2002). This has lead to millet grain yields <100 kg ha^{-1} after just one year of cultivation, a rate of degradation which is never observed in traditional farmers fields. The chemical processes involved in this degradation process – acidification and P immobilization – are not taken into account by APSIM. Hence, such 'control' treatments, besides not being representative of low input farmer field conditions, cannot be used for model performance evaluation. In practice, it is therefore better to select a control treatment with organic amendment inputs that are as low as possible yet sufficient to prevent rapid soil chemical degradation as well as representative of unfertilized farmer fields. In experiment I, the lowest input treatment consists of a low application rate of both manure (300 kg ha^{-1}) and crop residue (300 kg ha^{-1}). Such rates are fairly close to the amount of residue (Baidu-Forson, 1995) and manure present in farmer fields at the start of the rainy season (May–June). De Rouw and Rajot (2004) estimated that passing herds leave behind about 100 kg ha^{-1} of dung. The lowest input treatment R1F1M1 of experiment I may therefore be considered as an appropriate control treatment.

4.2. Performance of the model

One may consider that the APSIM model reasonably predicted the temporal variations of PAW measured during experiment I across the 27 combinations of manure, residue and mineral fertilizer applications (Fig. 4). Indeed, the average error in predicted volumetric water content was only 0.8–1.8% over the entire rooting depth. As PAW is the main water related factor affecting growth, this result is an essential step toward the use of the APSIM model in climate and fertility scenario analysis for decision support in Sahelian environments.

Water and N stress as simulated by the model were in agreement with expectations. In fact, 1994 was a very wet year (146% of long term annual average) and did not result in water stress for any treatment. Several heavy rainfall events that occurred in the same year resulted in substantial drainage and nitrogen leaching that affected even the high fertilized treatment. In 1995 near average rainfall (89% of annual long term average) probably caused some water shortage. Simulation results indicated that water stress occurred for the high fertilized treatments that developed more biomass and needed more water as opposed to the low fertilized ones. Despite much drier conditions in 1995, with water stress for the high fertilized treatment, measured grain yields were higher in 1995 than in 1994 (Fig. 6b). This may have resulted from the occurrence of a N stress, as predicted by the model for all treatments in 1994, thereby reducing yields. In 1995, there was no N stress for the high fertilized treatment and only limited water stress, which led to higher yields. Although measured total biomass was not greater in 1995 than in 1994, the model slightly underestimated the negative effect of N and/or water stress in 1995 on leave, stem and panicle biomass (Fig. 6a) but correctly reproduced the effect on grain yield. Crop growth simulation models based solely on water balance cannot capture and explain such water by nutrient interaction effects, which are nevertheless known to be central to the productivity of Sahelian millet-based cropping systems.

Given the complexity of experiment I involving 27 combinations of millet residue, cattle manure and mineral fertilizer during two years with contrasting rainfall, model performance in predicting biomass throughout the growing season was fairly good and final biomass and grain yield predictions were realistic. Simulated biomass and grain yield performance was about 20–30% (RMSE/average yield). This is of the same order of magnitude as commonly reported coefficients of variation of yields within farmer fields in the Sahelian Niger (Brouwer et al., 1993). Yet a close examination of the model performance showed that poor *d* index of agreement and RMSE values for biomass were observed mainly with respect to the treatments with a high residue application rate R3 (2700 kg ha^{-1}), the worst treatment being R3F3M3. Modeling errors may arise from model error and inputs/parameter errors (Loague and Green, 1991). On the other hand, measurement errors may lead to erroneous conclusions regarding model accuracy. In the present case it is assumed that measurement errors are small. The high coefficients of variation for measured grain and stover yields, ranging between 22% and 38%, do not reflect large measurement errors but reflect the large spatial variability typical of the Sahelian environment, even for experiments on research stations (Brouwer et al., 1993). Poor APSIM response with respect to R3 treatments in general could be explained by the fact that the model accounts only for the residue cover effect on the soil water balance and the impact of decomposing residue on the N balance. The millet stover having very low N content and a high C/N ratio, the model predicted N immobilization and a negative impact on millet yield at high residue application rates. In reality, it has been very well documented that the application of crop residue at rates up to 4 t ha^{-1} never results in a significant yield decrease. On the contrary, millet yield increases are generally reported in response to crop residue additions (see, e.g., Bationo and Mokwunye, 1991b). Experimental results from experiment I confirm this overall tendency (Akponikpe et al., 2008). This generally positive effect of residue on millet growth in the Sahel has been attributed to P mobility enhancement, a decrease in exchangeable Al and soil protection against wind erosion (Buerkert et al., 2000). These effects, and particularly the effect on P, are not currently taken into account by the APSIM-millet model. Hence, it may be concluded that the APSIM model performs satisfactorily for simulating millet response to fertilizer and manure when P is not limiting, but only for low rates of crop residue application ($\leq$900 kg ha^{-1} crop residue) (Fig. 7).

4.3. Long term N input scenario analysis and recommendations

Based on the two-year dataset of experiment I, grain yield can be expressed as a monotonously increasing function of N application rate, whether N is applied through manure or fertilizer (Fig. 7). The response is, however, year-specific. Hence, in order to draw more general recommendations regarding N management, it was necessary to evaluate millet response to N over a wider range of climatic conditions. This was achieved by running the validated model over the 1983–2005 period, which covers a wide range of annual rainfall, including an extreme dry year (1984) and a very wet year (1994).

The worst years, giving the lowest grain yield, were 1984 and 2000 for treatments for which the N application rate exceeded 15 kg N ha^{-1}. This can be explained by the fact that 1984 and 2000 were the driest years on record with 260 an 393 mm of annual rainfall (approximately all of which fell during the cropping in season), respectively. In these extreme dry years, low input treatments appear to perform slightly better than high input treatments given that water stress is more severe in the latter and N is not a strongly limiting factor. Bationo et al. (1993) also reported a drastically reduced millet yield in fertilized plots (30 kg N ha^{-1} + 17 kg P ha^{-1} + 25 kg K ha^{-1}) at Sadoré in 1984. For low N input (<15 kg N ha^{-1}), 1988 and 1994 lead to low yields (Fig. 1). These 2 years are the wettest years on record, with 700 and 794 mm annual rainfall, respectively. Wetter years often differ from normal years by the occurrence of many large rainfall events exceeding 30 mm per day (8 and 9 for 1988 and 1994, respectively, Fig. 1). Due to the sandy texture of the soils, these heavy storms lead to N leaching. Hence, N deficiency strongly limits yields on low N input treatments in wet years. These contrasted observations between the high and low N input treatments highlight the fact that water and N stress alternate between years and treatments in limiting yield.

The best years (resulting in the highest grain yield) were identified as 2003 under low N input conditions, 1990 and 1992 under medium intensification and 2002 under high intensification (Fig. 1). The annual rainfall of these years was close to long term average (550 mm), and the number of rainfall events was high (>29) with a limited number of heavy ones (<6). The fact that best yields are achieved during years with well distributed, near average rainfall independently of the intensification level seems to indicate that the good performance of these years had mostly to do with rainfall distribution, providing adequate water supply without inducing excessive N losses.

In subsistence millet farming systems, fertilization recommendations should be geared towards yield stability and achievement of a minimum 'guaranteed' grain yield each year, thereby reducing risk for small-holder farmers (Fussell et al., 1987; Brouwer et al., 1993). Based on the simulation results, inter-annual yield variability steadily increases at N application rates >25 kg N ha^{-1} (Fig. 8). This is consistent with the literature (Subbarao et al., 1999). Equally important, one observes a maximum in the minimum 'guaranteed' yield for a N application rate of 15 kg ha^{-1}. At that rate, yield is guaranteed to be at least 402 kg ha^{-1} every year, with a long term average grain yield of 605 kg ha^{-1}. Both the minimum and average yields are substantially higher (72 and 38%) than the zero N treatment, without inducing additional inter-annual variability. At rates >15 kg N ha^{-1}, intensification becomes increasingly riskier given the higher inter-annual variability and lower minimum guaranteed yield. This becomes very marked at rates >55 kg N ha^{-1}. At those high N rates, the N use efficiency (grain produced per unit N added) of any additional added N becomes marginal. Hence, it may be concluded from these simulations that, although the previous N fertilization recommendation of 30 kg N ha^{-1} allows to substantially increase both minimum and long term yields without exaggeratedly increasing inter-annual variability compared to no N input, it is not the most appropriate from a small-holder subsistence farming perspective. The application of 15 kg N ha^{-1} seems more appropriate as it guarantees a higher minimum yield in worst years, thereby reducing the vulnerability of small-holder farmers.

5. Conclusions

Following a calibration with independent datasets, the APSIM model was found able to satisfactorily predict millet response to combined fertility management practices for a Sahelian millet genotype under Sahelian environmental conditions. It may be used for decision support purposes regarding fertilizer and manure management for limited crop residue application rates (≤900 kg ha^{-1}) and when P is supplied proportionately to the N. The model reproduced well the measured average millet grain yield response trend to N inputs and was able to adequately reproduce the water by nutrient interaction as reflected in the overall higher observed grain yield in 1995 compared to 1994, despite the higher rainfall in 1994. This highlights the importance of considering water and nutrient interactions for modeling crop production, even for environments for which water is (often wrongly) considered as the main constraint. In addition, although crop simulation models based on water balance alone may provide first order estimates of crop yields at a regional scale, such models are clearly inadequate for developing management strategies at the local scale where differences in soil fertility and amendment types and rates of application will strongly interact with water supply. A 23-year, long term simulation with the validated APSIM model showed that moderate N application (15 kg N ha^{-1}) improves both the long term average and the minimum guaranteed yield without increasing inter-annual variability compared to no N input. Although it does imply a lower average yield than the current fertilizer recommendation (30 kg N ha^{-1}), the application of 15 kg N ha^{-1} appears more appropriate for small-holder, subsistence farmers as it guarantees higher minimum yield in worst years, thereby reducing their vulnerability.

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