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Millet response to water and soil fertility management in the Sahelian Niger : experiments and modeling

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To my late parents who showed me the path to success and encouraged me in my adventure of post-graduate and Doctoral studies.
Here is the outcome but you are no more there
to physically celebrate.

P. Douffodji Akponikpè: "*B'ina ba ku, a f'eeru boju . . .* "
C. Goyikpo Béhanzin-Akponikpè: "*Vi de kon, zo ma na ci.*"

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caused by my long absence from home.

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us in the course of this work.

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It seems always impossible until it is done.

Nelson Mandela

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P. B. Irénikatché Akponikpè

Summary

In the 400-600 mm annual rainfall zone of the Sahel, soil fertility is the main determinant of yield in rainfed millet cropping systems in all but the driest years. Numerous on-farm and on-station experiments have addressed the issue of improving soil fertility. Yet the widespread use of the experimental results is restricted by the highly site-specific millet response to fertility management practices due to high spatially variable soil properties as well as high intra- and inter-annual rainfall variability. Mathematical soil-crop growth simulation models could therefore suitably complement experimental research to support decision making regarding soil fertility under variable rainwater supply conditions. The objective of this thesis was therefore to develop the biophysical basis for the use of crop-soil models in decision support regarding water and soil fertility management and risk mitigation strategies in rainfed millet-based systems of Sahelian Niger. Because farmers rely on multiple cultivars with variable length of growing cycle due to sensitivity to temperature and photoperiod as part of their risk management strategies we first characterized seven Sahelian millet genotypes and parameterized the Agricultural Production Systems Simulator (APSIM-millet model). The cultivars include three improved cultivars (CIVT, ICMV-IS-89305, ZATIB) and four landraces (Ankoutes, Hainikirey, Maewa and Zongo). Our research showed that only one of the cultivars, Maewa, was very photosensitive contrary to the six others. The majority of the agronomic state variables (leaf number, leaf area, biomass and grain yield) were negatively affected by late sowing (associated with lower air temperatures). This characterization enabled to compute for the first time in the Sahel the principal eco-physiological or genetic millet parameters (thermal times of development phases, leaf area dynamics) of crop growth models (e.g. APSIM, DSSAT). To gain confidence in the use of the APSIM model for decision support in the Sahelian environment, it was successfully tested to reproduce the agronomic state variables under non-limiting water and nutrient supply conditions. Moreover the APSIM model satisfactorily reproduced the millet CIVT cultivar response to water x N interaction from the combined application of crop residue, cattle manure and mineral fertilizer during two years and for contrasted rainfall conditions. Using the model with site and cultivar specific parameterization, we implemented two applications for decision support. A 23-year, long term factorial numerical experiment showed that a moderate N application of 15 kg N ha^{-1} is more appropriate for smallholder, subsistence farmers than the usual 30 kg N ha^{-1} recommendation. Although it implies a lower long term average yield than at 30 kg N ha^{-1}, the application of 15 kg N ha^{-1} guarantees both a higher minimum yield in extreme dry years and a lower inter-annual variability, thereby increasing food security and reducing farmers vulnerability. In the second model application, we integrated GIS information (land tenure, spatially distributed weather data, fertility management) and the APSIM model in a 12-year yield simulation to show that the spatial dispersion of fields of a household throughout the village territory (farmer risk management strategy) leads to more uniform yields across households and reduces the inter-annual yield variability in the Fakara region of Niger. Our research breaks the ground for several other applications of the use of crop-soil simulation models in millet-based systems in the Sahel, e.g. climate change impact and food crisis mitigation.

Résumé

Dans la zone Sahélienne avec 400 à 600 mm de précipitation annuelle, la fertilité des sols est le principal facteur déterminant des rendements du mil pluvial hormis lors des années plus sèches. De nombreuses expérimentations au champ et en station ont abordé la question de l'amélioration de la fertilité des sols. Cependant, l'extrapolation de ces résultats, et a forciori leur utilisation par les agriculteurs, est limitée par le fait que la réponse du mil à ces pratiques de fertilité dépend fortement des propriétés des sols très variables dans l'espace ainsi que de la pluviométrie annuelle et sa répartition intra-annuelle. Les modèles mathématiques et dynamiques de simulation de la croissance des plantes peuvent donc utilement compléter la recherche expérimentale pour l'aide à la décision en ce qui concerne la gestion de la fertilité des sols dans diverses conditions d'alimentation hydrique. L'objectif de cette thèse était donc de développer les bases biophysiques pour l'utilisation de modèles de croissance des cultures en vue de leur utilisation comme outils d'aide à la décision en matière de gestion de l'eau et la fertilité des sols dans les systèmes de culture à base de mil en zone sahélienne du Niger. Puisque les paysans utilisent de multiples variétés de mil avec des cycles de croissance variables en tant qu'élément dans leurs stratégies de gestion des risques, nous avons d'abord caractérisé sept génotypes de mil Sahelien en vue de la paramétrisation du model dynamique APSIM (Agricultural Production Systems Simulator). Trois variétés améliorées (CIVT, ICMV-IS-89305, ZATIB) et quatre variétés locales paysannes (Ankoutes, Hainikirey, Maewa et Zongo) ont été étudiées. Notre recherche a montré que seule une des variétés, l'écotype Maewa, est très photosensible contrairement aux six autres. La majorité des variables agronomiques (nombre de feuille, surface foliaire, biomasse et rendement en grain) ont été négativement affectées par un semis tardif (associés à des températures de l'air plus faibles). Cette caractérisation a permis de calculer pour la première fois au Sahel les principaux paramètres éco-physiologiques du mil (durée thermique des phases de développement, dynamique de la surface foliaire), indispensables aux modèles dynamiques de croissance des plantes tels qu'APSIM et DSSAT. Le modèle APSIM a permis de reproduire avec succès les variables agronomiques de 6 des 7 variétés de mil en condition non-limitante d'apport en eau et en nutriments. De plus, le modèle APSIM a reproduit de manière satisfaisante la réponse de la variété améliorée CIVT à l'interaction de l'eau et de l'azote suite à l'apport combiné de résidus de récolte, de fumier de bétail et d'engrais minéral sur deux années ayant des pluviométries contrastées. Ceci a permis de renforcer la confiance dans l'utilisation du modèle APSIM comme outil d'aide à la décision dans l'environnement Sahélien. Sur base du modèle APSIM ainsi paramétrisé pour des conditions spécifiques de site et de variété, nous avons développé deux applications en matière d'aide à la décision. Une expérimentation factorielle numérique à long terme (23 ans) a révélé que l'application d'une dose modérée d'azote (15 kg N ha^{-1}) est plus appropriée dans le contexte d'une agriculture de subsistance que la recommandation habituelle de 30 kg N ha^{-1}. Bien qu'elle implique un rendement moyen à long terme inférieur à celui obtenu avec 30 kg N ha^{-1}, l'application de 15 kg N ha^{-1} garantit un plus grand rendement minimum pendant les années sèches extrêmes et une variabilité inter-annuelle plus faible, ce qui permet de garantir une meilleure sécurité alimentaire tout en réduisant la vulnérabilité des paysans. Dans la deuxième application du modèle, nous avons intégré des données SIG (parcellaire villageois, données climatiques et de pratiques de gestion de fertilité distribuées dans l'espace) et le modèle APSIM dans une simulation de rendement de mil sur 12 années. Ceci a permis de montrer que la dispersion spatiale des champs d'un ménage dans le terroir villageois (stratégie paysanne de gestion du risque) permet l'obtention de rendements plus uniformes entre ménages au sein du même village et de réduire la variabilité inter-annuelle des rendements de chaque ménage dans la région de Fakara au Niger. Notre recherche ouvre la voie à plusieurs autres applications de l'utilisation des modèles dynamiques de croissance des plantes dans les systèmes à base de mil au Sahel, par exemple dans l'étude de l'impact des changements climatiques et de prévention des crises alimentaires.

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List of Acronyms and variables

ACMAD	African Center of Meteorological Applications for Development
AGRHYMET	Centre Régional de Formation et d'Application en Agrométéorologie et Hydrologie Opérationnelle
AHP	ammonium hydrogen phosphate
APSIM	Agricultural Production Systems Simulator
APSRU	Agricultural Productions Systems Research Unit
APSWIM	APSIM soil water module based on Richard's equation
Bdc	broadcast
BJ104	a millet cultivar from India
BMELIB	Bayesian maximum entropy library tools (Christakos et al., 2002)
CAN	calcium ammonium nitrate (26% N, fertilizer)
CEC	cation exchange capacity
CERES	Crop Environment Resource Synthesis
CH	convex hull (area of the smallest bounding polygon which surrounds all the fields owned by a given household, used as field spatial dispersion index)
CIRAD	Centre de coopération internationale en recherche agronomique pour le développement
CIVT	Composite Inter-varietal de Tarna, selected by INRAN-Niger (millet cultivar)
CLIMAG-WA	Climate Prediction and Agriculture, West-Africa
CR	crop residue (millet if not specified)
CRESA	Centre Régional d'Enseignement Spécialisé en Agriculture
CropSyst	Cropping Systems Simulation Model
CSM	cropping system model
CV	coefficient of variation
CWC	critical volumetric water content (m^3 m^{-3})
D	planting density (hill ha^{-1})
DAS	days after sowing
df	degree of freedom
DHC	diagnostic hydrique des cultures
DM	dry matter
DSM	time from sowing to maturity (days)
DSS	Decision Support System

DSSAT	Decision Support System for Agrotechnology Transfer
DST	Decision Support Tool
EF	modeling efficiency
F	mineral fertilizer (F1, F2, F3 unfertilized control, 15 kg ha^{-1} N + 4.4 kg ha^{-1} P and 45 kg ha^{-1} N + 13.1 kg ha^{-1} P, respectively)
FAO	(United Nations) Food and Agricultural Organization
FDM	feacal dry matter
Fert	fertilizer
FG	fertility gradient around village homestead
FM	farmyard manure
GCM	global circulation model
GIS	Geographical Information System
GTP-model	genotype x temperature x photoperiod interaction model
GW	individual grain mass (kg $grain^{-1}$).
HKB	millet cultivar
IBSNAT	International Benchmark Sites Network for Agrotechnology Transfer
ICMV-IS	Breeding selection by ICRISAT-Niger from 3-4HK B-78, Souna-3 and CIVT (millet cultivar)
ICRISAT	International Crops Research Institute for the Semi-Arid Tropics
ILRI	International Livestock Research Institute
INM	integrated nutrient management
INRA	Institut National de la Recherche Agronomique, France
INRAN	Institut National de Recherche Agronomique du Niger
IRD	Institut de Recherche pour le Développement
ISC	ICRISAT Sahelian Center, Sadoré
J	drainage flux (mm day^{-1})
K	Potassium (kg ha^{-1})
LAI	leaf area index (m^2 m^{-2})
LAImax	maximum leaf area index or crop during the season (m^2 m^{-2})
M	manure (M1, M2, M3 cattle manure application at 300, 900 and 2700 kg ha^{-1} respectively)
M9D3	a millet cultivar from Mali
Man	manure (cattle manure if not specified)
MC	manure corralled
ML	maximum likelihood
MX001	a millet cultivar
N	Nitrogen (kg ha^{-1})
NG	or NGH number of grains per panicle or head
NPK	N15P15K15 fertilizer
NPP	number of productive panicles per hill (panicle $hill^{-1}$)
ns	not significant
OC	organic carbon (%)
OLS	ordinary least squares
P	Phosphorus (kg ha^{-1})
P	probability
PAPR50	partially acidulated at 50% phosphate rock

PAW	plant available water (mm)
PEST	Model-Independent Parameter Estimation tool (Doherty, 2004)
PFP	partial factor productivity (kg grain kg^{-1} factor)
PI	panicle initiation
PKP	or PFP K, partial potassium (K) productivity (kg grain kg^{-1} K)
PNP	or PFP N, partial nitrogen (N) productivity (kg grain kg^{-1} N)
PPP	or PFP P, partial phosphorus (P) productivity (kg grain kg^{-1} P)
Prob.	Probability
R	residue (M1, M2, M3 crop residue application at 300, 900 and 2700 kg ha^{-1} respectively)
R^2	square of the linear coefficient of correlation
Res	residue
Residue2	APSIM 3.6 residue module
RMSE	root mean square error
RP	rock phosphate
RP	rock phosphate
s.e.d	standard error of the (mean) difference
S1, S2, S3, S4	sowing dates (Chapter 3) on 19 April, 19 May, 18 June and 19 July respectively in 2005
SARRA	Système d'Analyse Régional des Risques Agroclimatiques
SARRA-H	Système d'Analyse Régional des Risques Agroclimatiques-Habillé
sd or SD	standard deviation
SD_ BM_ HD	inter-annual, standard deviation over years of household biomass yield relative to the same household average yield (over years)
SD_ BM_ TR	inter-annual, standard deviation over years of household biomass yield relative to the average yield across the village territory
SD_ GR_ HD	inter-annual, standard deviation over years of household grain yield relative to the same household average yield (over years)
SD_ GR_ TR	inter-annual, standard deviation over years of household grain yield relative to the average yield across the village territory
SOC	soil organic carbon
SoilN2	APSIM Nitrogen module
SoilP	APSIM phosphorus module
Soilwat2	APSIM soil water cascading layer module
SOM	soil organic matter
SSP	single super phosphate (18% P2O5, fertilizer)
STICS	Simulateur mulTIdisciplinaire pour les Cultures Standards
SurfaceOM	APSIM surface organic matter (initially "manure" and "residue2" module)
Tbase	base cardinal temperature (°C)
TDM	total dry matter
Tmax	maximum cardinal temperature (°C)
Tmax	maximum daily temperature (°C)
Tmin	minimum daily temperature (°C)
Topt	optimum cardinal temperature (°C)
TSP	triple super phosphate

TT	thermal time (°C day)
USG	urea super granule
v.r.	variance ration
VWC	volumetric water content (m^3 m^{-3})
WUE	water use efficiency (kg ha^{-1} mm^{-1})
Y	grain yield (kg ha^{-1})
ZATIB	Breeding selection by INRAN-Niger from Zanfarwa and Tchin-Bijini ecotypes (millet cultivar)
θ	volumetric water content (m^3 m^{-3})

APSIM parameters centred to this thesis and means of determination

Parameter	Description	Unit	Source[1]
APP	actual photoperiod of a given day	h	dir. meas.
bd	soil layer bulk density	Mg m^{-3}	dir. meas.
BPP	base photoperiod	h	default
cn_red	reduction in cn2_bare due to cover	-	fixed
cn2_bare	bare soil runoff curve number	-	fixed
cona	stage-2 soil evaporation coefficient	-	calibrat.
dul	drained upper limit	m^3 m^{-3}	calibrat.
fbiom	non-inert fraction of carbon in microbial products	-	default
finert	inert fraction of organic carbon	-	default
grain_gth_rate	grain growth rate	mg $grain^{-1}$ day^{-1}	calibrat.
head_grain_ no_max	maximum grain number per head	-	dir. meas.
kl	rate of soil water extraction	-	default
leaf_app_rate2	leaf appearance rate or TLA	$^\circ$C day $leaf^{-1}$	dir. meas.
ll	millet water lower limit	m^3 m^{-3}	default
ll15	soil lower limit (water content at -15 bar pressure head)	m^3 m^{-3}	dir. meas.
manure_pot_ decomp_rate	cattle manure potential decomposition rate	day^{-1}	ind. meas.

Parameter	Description	Unit	Source[(1)]
nh4ppm	(initial) ammonium-N	mg m^{-3}	dir. meas.
no3_diff_const	time constant for N millet uptake by diffusion	day	default
no3ppm	(initial) nitrate-N	mg m^{-3}	dir. meas.
pot_decomp_rate	millet residue potential decomposition rate	day^{-1}	ind. meas.
pp_endjuv_ to_init	thermal photoperiod sensitivity or PPS	°C day h^{-1}	default
PPS	photoperiod sensitivity or pp_endjuv_to_init	°C day h^{-1}	default
salb	soil albedo	-	default
sat	saturated volumetric water content	m^3 m^{-3}	ind. meas.
soil_cn soil	C/N ratio	-	dir. meas.
swcon	layer drainage rate coefficient	-	calibrat.
T_EJ_PI	time from end juvenile to panicle initiation	°C day	ind. meas.
T_EM_EJ	thermal time from emergence to end juvenile or tt_emerg_to_endjuv	°C day	ind. meas.
T_PI	time to panicle initiation	°C day	ind. meas.
TLA	thermal time for leaf appearance (fully expanded) or phyllochron or leaf_app_rate2	°C day $leaf^{-1}$	dir. meas.
TLI	thermal time for leaf initiation or plastochron	°C day $leaf^{-1}$	ind. meas.
TLN	total leaf number	-	dir. meas.
trans_eff_cf	transpiration use efficiency coefficient	kPa	default
tt_emerg_ to_endjuv	thermal time from emergence to end-juvenile phase or T_EM_EJ	°C day	ind. meas.
tt_flag_to_flower	thermal time from flag leaf to flowering	°C day	dir. meas.
tt_flag_ to_maturity	thermal time from flag leaf to maturity	°C day	dir. meas.
tt_flower_ to_start_grain	thermal time from flowering to start grain filling	°C day	default
tt_maturity_ to_ripe	thermal time from maturity to ripe	°C day	default
u	stage-1 soil evaporation coefficient	mm	calibrat.
y0	area of the largest leaf on an axis (main shoot or tiller)	mm^2	dir. meas.
y0_const	simple linear regression constant of the area of the largest leaf on an axis y0 on its total leaf number	mm^2	ind. meas.
y0_slope	simple linear regression slope of the area of the largest leaf on an axis y0 on its total leaf number	mm^2 $leaf^{-1}$	ind. meas.

(1)

dir. meas.: direct measurement

ind. meas.: indirect measurement (computed from direct measurement)

calibrat.: calibrated

default: default in APSIM millet

Chapter 1

Introduction and objectives

1.1 Context and justification

In Niger (West-Africa, Figure 1.1), pearl millet [*Pennisetum glaucum (L.) R.Br.*], the main staple food, dominates in the agricultural production system and contributes about 75% to the national cereal production (Ben-Mohamed *et al.*, 2002). The last 50 years have been characterized by a low annual millet production growth rate (0.6%) compared to the human population growth rate (3%) (Reardon *et al.*, 1997). Millet grain yields are low, usually below 500 kg ha^{-1} (De Rouw, 2004). The annual increase in the total national millet production is best explained (R^2 = 0.83) by the expansion of cropland rather than productivity increase (Figure 1.2).

Apart from pest damage, the low millet yields have been attributed to three major factors: (1) limited annual rainfall (300-600 mm), considering the high annual potential evapotranspiration (2000-2300 mm) associated with frequent drought spells and high inter-annual rainfall variability (Sivakumar *et al.*, 1993), (2) inherent low soil fertility (Bationo and Mokwunye, 1991a) and (3) limited use of external inputs (Shapiro and Sanders, 1998; Abdoulaye and Sanders, 2005). Much research has been undertaken to improve or simply maintain soil fertility (Klaij and Ntare, 1995; Bationo *et al.*, 1998; Lamers *et al.*, 1998; Sinaj *et al.*, 2001; Bationo and Buerkert, 2001), as well as improve water use efficiency (e.g. Payne *et al.*, 1991, 1992; Zaongo *et al.*, 1997; Payne, 1997, 2000), and nutrient use efficiency or both (e.g. Bationo *et al.*, 1990b). Research efforts provided the foundation for extension in Niger that formulated a set of recommendations regarding planting density (10.000 hill ha^{-1}) and nutrient management (30 kg N ha^{-1}, 13 kg P ha^{-1}), among others (Reddy, 1988; Klaij *et al.*, 1994). However, these recommendations have not been adopted (Lamers and Feil, 1995; Abdoulaye and Lowenberg-Deboer, 2000). There are multiple reasons for this, among which the weakness of extension services and incomplete exchange mechanisms between farmers-development-research and extension, as well as the complexity and heterogeneity of Sahelian production systems. Moreover the difference in priorities between researchers, who aim to

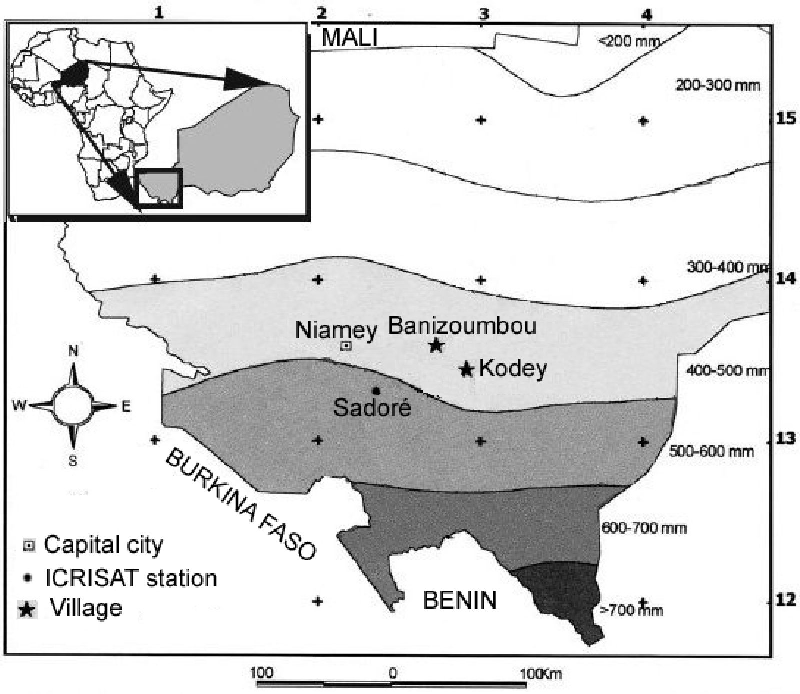

Figure 1.1. Geographical location and rainfall characteristics of the study sites in western Niger. Coordinates are in North and East degrees. [adapted from Schlecht *et al.* (2004)]

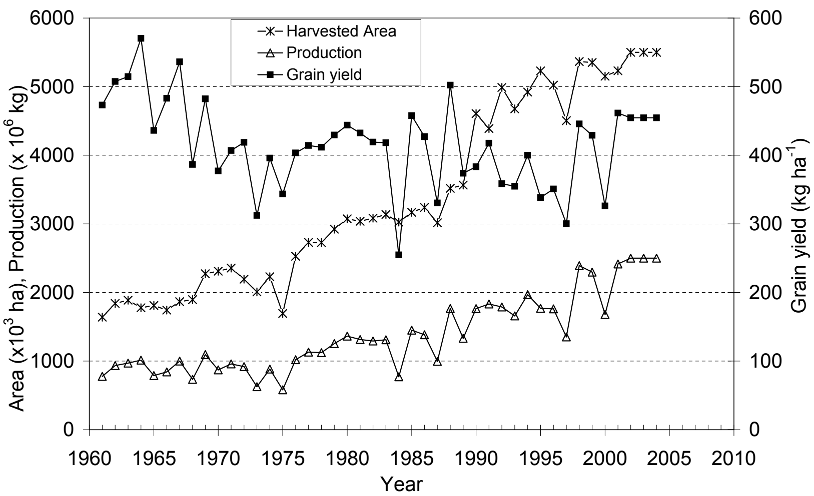

Figure 1.2. Annual total production, millet grain yield and total harvested area from 1961 to 2004 in Niger (FAO, 2007)

improve yields in average years, and Sahelian subsistence farmers, who seek to reduce the frequency of crop failure, could also explain the non-adoption of most innovations because the risks of yield losses were not reduced by the improved practices (De Rouw, 2004).

This situation calls for decision support tools (DSTs) such as mathematical crop-soil simulation models that are widely used to better understand and support decision making in agricultural systems (Gijsman *et al.*, 2002; Jones *et al.*, 2003; Keating *et al.*, 2003; Moeller *et al.*, 2007). The use of such DSTs enables to save time and expense from field and on-station trials and capitalize upon past research outcomes and farmers indigenous knowledge. This is particularly true in the Sahelian environment where research trial results are highly site and year-specific due to high spatial variability in soil properties and high inter- and intra-annual rainfall variability. Hence, crop-soil models can undoubtedly help with the interpretation of experimental data after careful calibration and validation. They can also be used in a prospective way in conjunction with field data to draw recommendations better adapted to the risk-minimization strategies used by farmers in these environments.

But so far, the use of crop models for decision support in millet-based systems in the Sahel is very limited. This is because the complexity and heterogeneity of the system call for detailed and dynamic simulation models which must be parameterized and tested with respect to millet water and nutrient responses but also with respect to the phenology and determinants of yield of the dominant cultivars found in the region. Indeed, farmers rely on multiple cultivars with variable length of growing cycle and sensitivity to photoperiodism as part of their risk management strategies. In addition, a number of improved cultivars have been introduced by national and international agricultural research organizations over the last decades, some of which potentially present an interest in famine mitigation strategies in case of late rains because of their short growth cycle (Ahmed *et al.*, 2000). Without cultivar-specific parameterization, calibration and validation, risk management strategies relying on this diversity of crop responses cannot be properly evaluated using crop-soil simulation models. Therefore prerequisites for the successful application of crop-soil models in millet-based systems in the Sahel are (1) the characterization of Sahelian millet genotypes, (2) an in-depth evaluation of crop-simulation models to respond satisfactorily to the main agricultural constraints in the area (water, N and P management, and the high variability in soil physical and chemical properties on short distances). This thesis will address only part of these prerequisites, by focusing on the characterization of common millet genotypes and on the water and N management in millet cropping systems.

1.2 Objectives of the thesis

The main goal of the research is to develop the biophysical basis for the use of crop-soil simulation models for decision support in the Sahel. The specific objectives are to:

1. Assess the main agricultural assets and constraints in the Sahel and the possibilities for the use of crop simulation models for decision making in order to alleviate them;

2. To characterize Sahelian millet varieties of Niger, from an ecophysiological and crop modeling point of view, under optimal water and nutrient conditions;

3. Evaluate the performance of the APSIM crop-soil simulation model for millet in Sahelian conditions under various genotypic, climatic and fertility management conditions;

4. Apply the APSIM crop soil simulation model to support decision making regarding water and soil fertility management and risk management strategies in the Sahelian Niger using recent and innovative tools for agricultural system analysis such as long term numerical simulation experiments and GIS.

1.3 Methodological overview

This thesis is the outcome of the combination of many disciplines and methodological approaches. Disciplines implemented were agronomy, eco-physiology, soil hydrology, applied mathematics and computer programming among others. In terms of methodology, we made use of literature review (Objective 1, chapter 2), on-station experiments at ICRISAT Sahelian center (Sadoré), farmer fields system analysis and characterization in the Fakara region (Niger) and numerical computer modeling. On-station experiments comprised both self designed and implemented experiments (Objective 2, chapter 3) and the capitalization of past on-station experimental data (chapter 4 and 5)(Table 1.1). These experiments served to either parameterize or calibrate the APSIM model or to validate it in order to gain confidence in its use as a decision making tool in the Sahelian Niger. Farmer fields characterization in the Fakara region focused mainly on the soil physical (Weynants, 2005) and chemical (Ska, 2005) properties as well as rainfall conditions (Van Vyve, 2006) and were implemented as bio-engineering Master (MSc.) research thesis. The outcome of these studies, though not presented in detail in the present thesis, provided the

Table 1.1. Overview of the experiments reported in the thesis. All of them took place at ICRISAT Sahelian center at Sadoré, Niger

Experiment and description	Year	Water and nutrient conditions	Cultivar(s) number and name	Author	Use in the thesis
Millet characterization (sowing date effect of millet growth and yield)	2005	Non-limiting water (irrigation) and nutrient supply	7 with 4 landraces[a] and 3 improved [b]	Design, implementation and data analysis (ourself)	Millet parameterization and APSIM validation (Chapter 3, 5 and 6)
Integrated nutrient management for millet combining residue, manure and mineral fertilizer	1994, 1995	Rainfed	CIVT	Design, implementation (Michels K.), data analysis (ourself)	Millet response to fertility management (Chapter 4) and APSIM validation (Chapter 5)
Bare soil water balance	1996	Rainfed	No crop	Design, implementation (Bielders C.) , data analysis (ourself)	Calibration of water dynamics in APSIM (Chapter 5)

[a] Ankoutes, Hainikirey, Maewa, Zongo
[b] CIVT, ICMV-IS89305, ZATIB

basis for the understanding and the numerical modeling of some farmer risk coping strategies (Minet, 2007)(chapter 6).

1.4 Outline of the thesis

The thesis is made up of 5 main independent sections presented in journal paper format, all references being gathered at the end of the document. Chapter 2 is a review of the millet production constraints in the Sahelian Niger, the main research outcomes to solve them and the possibilities to take advantage from the available information for the establishment of decision support tools. Chapter 3 presents the ecophysiological characterization of seven millet cultivars and the performance of the APSIM model to simulate the growth and yields of these cultivars sown on four sowing dates in 2005. Chapter 4 deals with an integrated nutrient management experiment for pearl millet using combined crop residue, cattle manure and mineral fertilizer application. This experiment served to validate the APSIM model under various fertility management practices, which is presented in chapter 5 along with the use of the model to support decision making regarding N management for millet in Niger. The last section (chapter 6) reports on the use of the APSIM model combined with GIS to evaluate a farmers' strategy for agro-climatic risk management in a context of high spatial rainfall variability.

Chapter 2

Crop modeling for decision support in millet-based systems in the Sahel: a challenge

Abstract

Sahelian farmers' agricultural management practices are reviewed with an emphasis on Niger and pearl millet. Remarkable results derived from research works to improve crop productivity are presented and analyzed with regard to the main agricultural constraints. Potential and currently used crop/soil modeling tools are presented and compared in terms of relevance for use as decision support tools in such a particular environment. This shows that crop modeling in millet-based agricultural system of the Sahel should be addressed with an integrated approach that can handle the multiple and usually connected agricultural constraints. Recommendations are made regarding the relevant aspects that crop/soil simulation models must take into account for successful and reliable use as decision support tools (DSTs) in the Sahel.

Keywords: millet-based systems, Sahel, decision support, crop-soil models, rainfall, soil fertility

2.1 Introduction

Small-holder farmers in the Sahelian zone of sub-Saharan Africa are facing difficult times as a result of productivity levels that are often low. Millet grain yields are often below 500 kg ha^{-1} (De Rouw, 2004). Crop yields are strongly dependent on, and constrained by what has been recently recognized (after many decades of blaming only water stress) as the most important asset - soil fertility. The unfavorable climate and low fertility create intense pressure on land even at relatively low population densities (Reardon *et al.*, 1997). Much research has been undertaken in the area but these constraints are still impeding the development of agricultural systems. This situation calls for tools that can support decision making. Such decision support tools (DSTs) can assist with the diagnosis and analysis of problems and opportunities related to water, soil fertility, and farmers indigenous practices. Several DSTs have been developed over the past decades; they range from simple best-bet options tables to sophisticated computer models.

A computer model is a simplified representation of reality with which we can compute outcomes without having to perform actual experiments. Biophysical models can be used to predict crop yield under different management strategies, as well as individual land properties or characteristics that are important components of yield, such as moisture supply, nutrient supply, and radiation balance.

The objective of this review is to analyze agricultural constraints for millet-based systems in the Sahelian region with respect to local farmers' practices and research outcomes. An overview of potential crop simulation models or currently used in semi-arid Africa is given. And finally the role that these models may play in such an environment is discussed.

2.2 Agricultural constraints in millet-based cropping systems in the Sahel

2.2.1 Rainfall uncertainty and variability in time and space

The general atmospheric circulation is a major factor influencing climate variation in west Africa. In Niger, the single-peak rainy season occurs in the period from May to September, with the remainder of the year dry. The length of the rainy season ranges from 60 days (250 mm year^{-1} isohyet) to 120 days (750 mm year $^{-1}$ isohyet). Millet is grown throughout the semi-arid zone, but is dominant within the 250-750 mm year^{-1} zone (Hoogmoed and Klaij, 1990). The annual potential evapotranspiration is high (2000 - 2300 mm year^{-1}) (Sivakumar *et al.*, 1993).

Moreover, a long term rainfall trend towards aridification was reported especially for northern rainfall stations and a comparison of different annual rainfall datasets shows that the isohyets have shifted 100-150 km southward since the 1960s (Sivakumar *et al.*, 1993). A close relationship between the Sahelian rainfall decrease and the reduction in the number of rainy days has been confirmed by Le Barbé and Lebel (1997). They observed a decrease in both the seasonal amount and number of rainfall events of about 25%. But recently, this trend towards aridification became a very controversial issue. While some authors reported the drought to be ending since the 1990 (e.g. Ozer *et al.*, 2003), or being simply an artifact of changing station networks (e.g. Chappell and Agnew, 2004) others as L'hote *et al.* (2002, 2003), Dai *et al.* (2004) and Hulme (2001) comfirmed it to be real and continuing.

Beside the long term trend, the temporal variability of rainfall is very high on the annual, monthly and daily time scales. The monthly rainfall variability is more distinct since rainfall occurs only during the 3-5 summer months. More crucial to agriculture is the daily variability. The average amount of rain per rainy day increases from 9.7 to 14.4 mm during the course of the rainy season, while the standard deviation increased at the same time from 7.6 to 11.1 mm. The mean duration between successive rain events progressively decreases during the wet season from 6 to 2 days. Mean maxima per rainy day in July and August are 45 mm day^{-1} and 48 mm day^{-1} respectively (Sivakumar *et al.*, 1993).

The Sahelian zone is characterized by a strong North-South annual rainfall gradient, with 1 mm decrease on average for every km. Beside this general latidunal trend, annual differences of 200-300 mm may occur in any directions within a radius of only 100 km. So spatial rainfall variability is higher at a local scale than at regional scale. The strong local scale rainfall variability is a factor farmers have to deal with in the Sahel and farmer's fields are found to be dispersed within 1-5 km distance (Graef and Haigis, 2001). At ICRISAT Sahelian center, total annual rainfall in 1995 ranged from 440 to 553 mm over only 2.5 km distance, while in 1996 it ranges from 503 to 554 mm over 0.8 km distance which correspond to maximum gradients of 42 and 64 mm km^{-1}, respectively (Graef, 2000). The same author mentioned that single rainfall gradients may exceed 20 mm over 3.2 km distance during a single event.

2.2.2 Poor and highly variable soil physical and chemical characteristics

Based on data from the Fakara region (Hiernaux and Ayantunde, 2004) and ICRISAT Sahelian center, Sadoré (Lu *et al.*, 2004), the soils were classified as sandy, with more than 90% sand in the A horizon (West *et al.*, 1984). Soils have a pH-water of 4.5 to 6.3, CEC of 0.8 to 7.0 meq/100g, organic matter content of 0.1 to 0.80%, total N of 100 to 300 mg kg^{-1} and total P 0.7 to 5.5 mg kg^{-1}. Soil water at field capacity is of the order of 0.10 cm^3 cm^{-3} (Klaij and Vachaud, 1992). High variability were reported over short distances (2 m) (Geiger and Manu, 1993; Manu *et al.*, 1996; Rockstrom, 1999; Voortman *et al.*, 2004).

The soil are of structureless class with high percentage of coarse sand particle (Hoogmoed and Klaij, 1990). Differences in soil properties are thought to be caused by differential wind and water erosion and deposition, growth of trees and shrubs before clearing for cultivation, trees left standing such as *Faidherbia albida*, termite activity, differential leaching, and/or human activity (including uneven application of manure, location of village sites and refuse heaps, and burning of cleared vegetation) (Miedema *et al.*, 1994; Geiger *et al.*, 1994; Gérard and Buerkert, 1999; De Rouw and Rajot, 2004b).

2.2.3 Yield variability in space and time

Millet germinates uniformly across fields, but 1-2 weeks after emergence, differences in growth occur (Scott-Wendt *et al.*, 1988a). This short-range variability results in low yields in farmers' field and experiments. Using a harvest scoring technique in 1993, on a 40 x 60 m plot, grain yield in the sub-plots (4 x 5 m) at the end of the growing season ranged from 0.02 to 1.38 t ha^{-1}, with an average of 0.64 t ha^{-1}. The total biomass measured in the sub-plots ranged from 0.16 to 4.50 t ha^{-1}, with an average value of 2.35 t ha^{-1} (Sterk *et al.*, 2004).

Many attempts were made to explain the cause of this large millet yield variability. Some authors have observed that often, although not consistently, millet growth is better on micro-high conditions and poorer in micro-low situations (Scott-Wendt *et al.*, 1988b; Geiger and Manu, 1993; Manu *et al.*, 1996). Scott-Wendt *et al.* (1988b) investigated a transect from very poorly growing to well-growing millet and observed that low yields were correlated with high Aluminium saturation levels and lower cation levels (Ca, Mg, and K). Voortman *et al.* (2004) showed that the proportion of the cations (Ca, Mg, K and Na) on the exchange complex, in combination with the Al saturation profile were the main source of spatial variability at this scale where these soil properties explained 82% of the millet yield variation. They pointed out that macronutrients N, P, K explained only a modest portion of millet yield spatial variability.

Termite activity was cited as another factor inducing spatial yield variability. According to Miedema *et al.* (1994) good growth sites were associated with a higher level of termite-derived pedofeatures (termites infillings) and termite amended groundmass features (bridged grain microstructures). They explained this by an enrichment of the soil surface with organic matter and fine clayey material as a result of termite activity which cause a better chemical fertility status and a better water holding capacity.

Inter-annual yield variation has been explained by rainfall pattern with the main determinants being the date of rain onset, number and length of dry spells, and water x nutrient interaction. In fact the period of rain onset is very wide (April to July), the average date (and standard deviation) of onset of the rainy season in Niamey is 12 June (18 days) while rain stops approximately at the same time every year at 27 September (12 days), causing late sowings to suffer from end of season water stress (Sivakumar, 1988, 1990). Frequent occurrence of dry spells were reported to impede millet developpement and yield establishment mainly during sensitive phenology stages such as flowering and grain filling (Sivakumar, 1992; Winkel *et al.*, 1997). Interaction between water and nutrient availability was frequently reported to explain millet yield variability between years. For instance, Gandah *et al.* (2000) observed that maximum yield was not observed at the same place in farmer fields every year (under the same fertility practice). Christianson *et al.* (1990) tried to explain millet grain yield as a function of N rate and annual or mid-season rainfall.

2.3 Farmer soil fertility management practices and research findings

2.3.1 Manure and corralling of livestock (on fields)

Smallholder farmers employ a range of technologies to enhance soil fertility, and manure is a cornerstone of many of the soil fertility management strategies they use. Manure is composed of all sort of feaces, urine, refuse fodder, vegetation added to the compost to trap urine, cooking waste and ash from cooking fire (Harris, 2002). Large cattle or small ruminant manure application is devoted to limited spots within farmers' fields and often applied (corralling livestock on field or transported farm yard manure) at very high application rates. Manure application was targeted to spots in only 30% of 307 fields surveyed by Schlecht *et al.* (2004) in a recent survey around Chikal, southwestern Niger.

Schlecht *et al.* (2004) collected data from southwestern Fulani (herders) and Zarma villages in southwestern Niger (Ticko, Kodey, Tigo-tegui, Banizoumbou) refarding corralling and manuring practices and found average application rates of 12.7 to 15.5 t ha^{-1} feacal dry matter (FDM) for cattle and 6.8 to 7.2 t ha^{-1} (FDM) for sheep and goats. Average manure application rates in Chikal were much lower, varying around 3.4 t ha^{-1} and 1.3 t ha^{-1} FDM for cattle and for small ruminants. Akponikpè (2005) found 0.05 to 4.9 t ha^{-1} in corralled spots and 0.0 to 1.0 t ha^{-1} in transported manure spots within farmers field in the same area (Kodey, Tigo-tegui, Bagoua, Banizoumbou) in 2004. The application amount varies according to the farmer cattle herd size and the extent and spatial homogeneity of application depends on his capacity to assure a good distribution of the manure in the spots during corralling or manure transportation.

Manuring of the same field or spot is normally repeated only every 3rd-5th year. In general, more farmers opt for the longer interval between applications than the shorter one (Schlecht *et al.*, 2004).

Manure received much scientific attention (Williams, 1999; Harris, 2002;

Table 2.1. Effect of application frequency and amount of manure (M) on millet grain yield in Sahelian West-africa. Most soils are arenosol. [adapted and completed from Schlecht *et al.* (2006)].

Amendment	Amount (kg ha^{-1})	Grain yield increase above control	Application Frequency and country	References
FM	5000	Millet: 99%	Once every 3 years (Burkina Faso)	Bationo and Mokwunye (1991a)
FM	20000	Millet: 302%	Once every 3 years (Burkina Faso)	Bationo and Mokwunye (1991a)
MC	2000	Millet: 1st year 350 kg ha^{-1}, 2nd year 90 kg ha^{-1}, 3rd year 190 kg ha^{-1}, 4th year 145 kg ha^{-1}	Once every 5 years (Niger)	Schlecht *et al.* (2004)
MC	4000	Millet: 1st year 500 kg ha^{-1}, 2nd year 177 kg ha^{-1}, 3rd year 240 kg ha^{-1}, 4th year 150 kg ha^{-1}	Once every 5 years (Niger)	Schlecht *et al.* (2004)
FM + SSP	5000 + 8.7 broadcast	Millet: 202%	Once every 3 years/SSP yearly (Niger)	Bationo and Mokwunye (1991a)
FM + Rock-phosphate	5000 + 39.3 broadcast	Millet: 163%	Once every 3 years/RP yearly (Burkina Faso)	Bationo and Mokwunye (1991a)
FM + NPK fertilizer	5000 + 100 broadcast	Millet: 150-700 kg ha^{-1}	Yearly (Burkina Faso)	Dugué (1998)

FM Farmyard manure, MC Manure corralled, SSP single super phosphate,

RP rock phosphate, NPK 15-15-15

Schlecht *et al.*, 2004). The effect of different manuring and corralling treatments on millet yield in the Sahel varies widely (Table 2.1). Having tested from 1997 to 2001 five rates of application of cattle manure, i.e., 2, 4, 6, 10, and 14 t ha^{-1} of fecal dry matter on a millet landrace, Schlecht *et al.* (2004) found that millet dry matter yields exceeded (on average over 4 consecutives years) the yield of the control by 779±84 kg ha^{-1} of grain and 1822±233 kg ha^{-1} of stover when 2 t ha^{-1} of manure were applied in the first year. The yield response of millet increased linearly to the rate of manure application in the first year, at least up to 14 t ha^{-1} of FDM. Additional on-farm trials from the same region extend the linear response up to an application rate of 21 t FDM ha^{-1} (Gerard, unpublished). Some on-farm experiments (Tigo, southwestern Niger) showed that the residual effect of manuring was still significant 3 years after application (6 t ha^{-1} manure + 2 t ha^{-1} crop residue), with grain yields of 527±56 kg DM ha^{-1} versus 298±54 kg DM ha^{-1} in the control (Schlecht *et al.*, 2004). Underlying beneficial effects of manure are increased soil porosity and aggregate stability, increased water infiltration and water holding capacity, decreased eolian soil losses, increased soil organic matter (SOM), pH, CEC and nutrient availability (e.g. Bationo and Mokwunye, 1991b; Buerkert and Hiernaux, 1998; Schlecht *et al.*, 2004). But the quality of manure produced by livestock and their effect on crop vary according to their diet (Powell *et al.*, 1994; Tittonell *et al.*, 2007). Other works have pointed out the beneficial effect associated with the application of urine during corralling (Powell *et al.*, 1998; Sangaré *et al.*, 2002).

Large manure application rates usually result in high nutrient loss on the acidic and sandy soils of Niger. On average, 1070 kg ha^{-1} of C, 91 kg ha^{-1} of N, 19 kg ha^{-1} of P were leached in a single year to depth between 1.5 and 2 m at high rates (9 to 10 t ha^{-1}) of manure application (Brouwer and Powell, 1998). They suggested application to be less than 2.8 t ha^{-1} on topographical lows (prone to high run-on and rainfall infiltration) and 2.5 t ha^{-1} on higher parts (prone to runoff and low rainfall infiltration) of farmer's field. But these recommendations do not take into account the highly variable quality of the manure (Harris, 2002) and its low availability in the area. One strategy to increase the nutrient efficiency, well known to farmers but labour demanding, is placement of the manure in planting pits (zaï) (Fatondji, 2002; Fatondji *et al.*, 2006).

2.3.2 Crop residues

Traditionally farmer remove millet residues from fields, after grain harvest, for household uses (fencing, fuel, animal feeding, bed or granary making) or sell them to herders (Baidu-Forson, 1995; Bationo *et al.*, 1995). So little crop

Table 2.2. Effect of application frequency and amount of millet crop residue (CR) on millet yield in Sahelian west-Africa. Most soils are arenosol [adapted and completed from Schlecht *et al.* (2006)].

Amendment	Amount (kg ha^{-1})	Grain yield increase above control	Application Frequency and country	References
CR	2000	20->100%	Annually (Burkina Faso)	Bationo *et al.* (1992, 1993)
CR	2000 (control: 500)	1st year 6%, 2nd year 20%, 3rd year 32−40%	Annually (Niger)	Buerkert *et al.* (2000, 2002)
CR	4000	Millet: 250%	Annually (Niger)	Bationo and Mokwunye (1991a)
CR	2000	1st year 20%, 2nd year 108%, 3rd year 283%	Annually (Niger)	Buerkert and Lamers (1999)
CR	All CR from last harvest	40−238%	Annually (8 years) (Niger)	Yamoah *et al.* (2002)
CR	4000 1st year and all CR from last harvest	up to 443%	Annually (6 years) (Niger)	Hafner *et al.* (1993b)
CR	1st year 2000 2nd year 6000 (control received noting since 4 years	TDM: 1st year 62%, 2nd year 192%	Annually (Niger)	Rebafka *et al.* (1994)
CR + fertilizer	4000 + 13 kg P ha^{-1} broadcast	790%	Annually (Niger)	Bationo and Mokwunye (1991a)
CR + fertilizer (SSP, urea, KCl)	4000 1st year and all CR from +13 P 30 N 25 K kg ha^{-1} last harvest	up to 1070%	Annually (6years) (Niger)	Hafner *et al.* (1993b)
CR + fertilizer	All CR from last harvest + 13 kg P ha^{-1} + 30 kg N ha^{-1} broadcast	90->400%	Annually (8 years) (Niger)	Yamoah *et al.* (2002)
CR + fertilizer	4000 1st year CR or all CR harvest + 17 P +30 N kg ha^{-1} (urea) +25K (KCl)	80->600%	Annually (Niger)	Bationo *et al.* (1993)
Millet CR + fertilizer (SSP)	1st year 2000 + 13 kg P ha^{-1}, 2nd year 6000 + 13 kg P ha^{-1}, (control received noting since 4 years	TDM: 1st year 266%, 2nd year 447%	Annually (Niger)	Rebafka *et al.* (1994)

CR millet crop residue, SSP single super phosphate residues are left on fields. Schlecht and Buerkert (2004) found in a recent survey in the Chikal territory, southwestern Niger, that mulching of crop residues was mainly practiced to fight wind erosion but was restricted to 36% of 307 individual farmers' fields given the alternative use of straw as livestock feed. Quantities of stover found on fields in the Sahel before millet sowing are less than 800 kg ha^{-1} and mostly inadequate for effective mulching (Baidu-Forson, 1995).

As it is encountered within farmer fields prior to sowing, crop residue has benefited from extended research attention. Especially long-term but also short-term application of crop residue (mulching) increases pearl millet yield, whereas their omission decreases yield immediately. Yield increase due to mulching throughout the region is summed up in Table 2.2. For Sahelian climatic conditions, the sandy soils of western Niger and application rates up to 4 t ha^{-1}, no depressive effect of crop residue on millet yield has ever been reported. Incorporation of crop residues gave higher yield compared to mulching or burning (Rebafka *et al.*, 1994). The mechanisms responsible for the positive effect of crop residue on crop are physical and chemical. Physical effects comprise: reduced nutrient loss by wind erosion that enhance seedling emergence and early growth (Michels *et al.*, 1995; Buerkert *et al.*, 2000; Bielders *et al.*, 2000, 2001, 2002), reduction in surface crusting, increased formation of stable aggregates improving soil porosity and water infiltration (Hoogmoed and Stroosnijder, 1984; Buerkert and Stern, 1995) and a decrease in soil surface temperature (Buerkert and Lamers, 1999; Buerkert *et al.*, 2000). Chemical mulching effects are related to increased exchangeable base content and cation exchange capacity (CEC), lower Al saturation, increase in plant available phosphorus and potassium, and P mobility (Kretzschmar *et al.*, 1991; Geiger *et al.*, 1992; Bationo *et al.*, 1993; Hafner *et al.*, 1993b; Rebafka *et al.*, 1994). The rate of crop residue generally tested in research or recommended are far higher than what is encountered in farmer fields before sowing and even exceed annual stover yield, which raises questions about their relevance.

2.3.3 Mineral fertilizer

The millet-based farming system in the Sahel is characterized by no or low inputs of fertilizer. Farmers usually mix small quantities of fertilizer with seed at sowing.

Because of the low availability of crop residue and manure in the Sahel, more attention was given by research to mineral fertilizer use in order to alleviate soil fertility constraints. Although some authors have reported large responses to K fertilizer (Rebafka *et al.*, 1994), mineral fertilizer strategies have generally focused on satisfying plant N and P requirements, the two most limiting nutrients (Bationo *et al.*, 2003). There is no positive response to N unless adequate P is supplied (Buerkert and Stern, 1995; Buerkert *et al.*, 2001). There were many research works done to prove the beneficial effect of N and mainly P fertilizer in the area and some are summarized in Table 2.3 (Christianson *et al.*, 1990; Bationo *et al.*, 1992; Bationo and Ntare, 2000; Subbarao *et al.*, 2000; Buerkert *et al.*, 2001; Yamoah *et al.*, 2002). Single superphosphate (SSP) applied annually at 13 kg P ha^{-1} effectively removed P deficiency on most cases. Rockphosphate (RP) from various regional sources (RP compacted with soluble fertilizer and partially acidulated phosphate rock (PAPR) have also been tested and shown to vary widely in their efficiency (Bationo *et al.*, 1990a; Bationo and Mokwunye, 1991a). Phosphorus-induced increases in millet yield have been shown to substantially increase with N application. Most research examined the immediate millet response of single or repeated application of soluble N and P and little is known about residual effects on plant growth over time, although this is crucial to predict adoption by smallholder farmers (Schlecht *et al.*, 2006). Moreover there is evidence that on weakly buffered Sahelian soils the sole use of mineral fertilizers may lead to rapid decrease in soil organic matter (SOM) and pH, thereby detrimentally affecting millet production. To be sustainable, any long-term application of mineral fertilizers to Sahelian soils will need to be combined with the application of organic matter.

2.3.4 Combined organic amendment(s) and mineral fertilizer

Although the effectiveness of manure, crop residue or fertilizers for improving soil fertility and crop yields has been demonstrated repeatedly through on-station and on-farm trials (e.g. Bationo and Mokwunye, 1991a,b; Brouwer and Powell, 1998), all these sources are limited for farmers' use by either availability (Palm *et al.*, 1997), competing uses (Bationo *et al.*, 1995; Lamers *et al.*, 1998) and price or financial risk (Shapiro and Sanders, 1998). Hence, an integrated nutrient management (INM) which relies on the use of multiple sources of nutrients sources (various organic and mineral fertilizer) is a necessity in order to achieve productive and sustainable agricultural systems (Palm *et al.*, 1997; Kimani *et al.*, 2003).

Additive, but also synergetic (more than proportional) effects have been reported in the literature as a result of the combined use of organic and inorganic amendments (Table 2.1, Table 2.2) (Bationo *et al.*, 1993; Hafner *et al.*, 1993b; Buerkert *et al.*, 2000; Kimetu *et al.*, 2004). In Niger, phosphorus use efficiency for millet (kg grain / kg applied P) was increased from 46 on plots fertilized with inorganic P to 86 on plots amended with inorganic N and P and millet crop residue (Bationo *et al.*, 2003). On average over a 9-year exper-

Table 2.3. Effect of application frequency and amount of mineral fertilizer on millet yield in Sahelian West-Africa. Most soils are arenosol. [adapted and completed from Schlecht *et al.* (2006)]

Amendment	Amount (kg ha^{-1})	Grain yield increase above control	Application Frequency and country	References
RP(applied in 1984)	39 (bdc)	34% (measured in 1988)	Not given (Niger)	Bationo and Mokwunye (1991a)
RP	130 (bdc)	76%	3-10 years (Niger)	Bationo *et al.* (1990a)
RP	130 (bdc)	TDM 38-172% (in year 3)	10 years (Niger)	Buerkert and Hiernaux (1998)
P seed coating (SSP, AHP etc.)	<0.5 mg P $seed^{-1}$	TDM: 30%, grain: 45%	Annually (Niger)	Rebafka *et al.* (1993)
SSP	13 (bdc)	TDM 24% over 4 years	Annually (W-Africa)	Buerkert and Hiernaux (1998)
SSP	8.7 (dbc)	102%	Annually (Niger)	Bationo and Mokwunye (1991a)
SSP	13 (bdc)	grain 168%, straw 120%	Annually (Niger)	Bationo and Mokwunye (1991a)
SSP	13.2 (bdc)	125%	Annually (Niger)	Bationo *et al.* (1992)
RP+ NPK	39 (bdc) + 4 P as NPK placed	TDM 51% over 4 years Range in year 3: 65-259%	3-early/NPK annually (W-Africa)	Buerkert *et al.* (2002)
N (urea) + 38 P (TSPa)	45, 90, 135 or 180 N	51, 104, 138, 103%	Annually (Niger)	Pandey *et al.* (2001b)
SSP + N(CAN)	45N + 13.2P	81%	Annually (Niger)	Sivakumar and Salaam (1999)
SSP + urea	13 (P)+30(N) (bdc)	50-> 300%	Annually (Niger)	Yamoah *et al.* (2002)
SSP + N(urea or CAN)	30N+13.2P hill placed / bdc	168% / 188%	Annually (Niger)	Bationo *et al.* (1992)
PAPR + (urea or CAN)	30N+13.2P bdc	188%	Annually (Niger)	Bationo *et al.* (1992)
N(urea), SSP), K(KCl)	17P +30N +25K	100- >400%	Annually (Niger)	Bationo *et al.* (1993)
P(SSP)+ N(urea) + K(KCl)	13P 30N 25 K	up to 381%	Annually (6 years) (Niger)	Hafner *et al.* (1993b)
N (CAN, urea, or USG) +K+P	15, 30 or 45 N + 13.2P + 25K (N banded or split)	300+ 1.70R+ 10.36N-0.41N2+ 0.07NxR (R^2adj. = 0.82)	Annually (Niger)	Christianson *et al.* (1990)
N(urea), P(SSP), K(KCl) x Density	0.5 hill m^{-2} 1 hill m^{-2} + 20N 2 hill m^{-2} + 40N 4 hill m^{-2} + 60N (all + 13.6P + 15 K)	Y = 1085 - 8.65N-51.13D-2.73R+ 0.071NxR +0.304DxR	Annually (Niger)	Bationo *et al.* (1990b))

SSP single super phosphate, TSP triple super phosphate, AHP ammonium hydrogen phosphate,
RP rock phosphate, PAPR50 partially acidulated at 50% phosphate rock,
USG urea super granule, bdc broadcast, TDM = total dry matter, NPK 15-15-15
N, P, K= rate kg ha^{-1} D= density (hill m^{-2}), R= rainfall during critical growth stage (mm)- July-August

iment, Yamoah *et al.* (2002) reported that millet grain yield increased from 320 kg ha^{-1} on control plots to 700, 900 and 1510 kg ha^{-1} on plots amended with residue, N+P fertilizer and residue+N+P fertilizer, respectively. Similar trends were reported for millet stover yield. Water use efficiency was raised from 0.78 kg grain ha^{-1} mm^{-1} for the control to 3.61 kg ha^{-1} mm^{-1} for the residue+fertilizer plots. Fertilizer use efficiency (kg grain kg^{-1} fertilizer) was 13.5 for the fertilized plots and increased to 27.6 upon the addition of residue. Yamoah *et al.* (2002) concluded that the residue+fertilizer treatment had the highest sustainability yield index. These synergetic effects may result from the side effects of using organic fertilizers, besides their role as nutrient providers: P mobility enhancement, decrease in exchangeable Al, enhancement of root growth, decreased surface temperature and soil penetration resistance, and soil protection against wind erosion (Buerkert *et al.*, 2000; Bielders *et al.*, 2000). A specific effect of INM is also to maximize nutrient use efficiency (Kimani *et al.*, 2003). In millet-based rainfed systems, this goes along with a strong increase in water use efficiency, as seasonal cumulative evapotranspiration is little affected by fertility management practices (Payne, 2000). Whereas fertilizers release their nutrients rather rapidly, manure or residue act as slow release fertilizers. In addition, they are a source of multiple nutrients, including micronutrients, supply carbon for soil micro-organisms involved in nutrient cycling, and may improve soil physical and chemical quality (Buerkert *et al.*, 2000; Esse *et al.*, 2001; Harris, 2002). The use of either crop residue or manure can buffer soil acidification resulting from fertilizer use, thereby enhancing fertilizer use efficiency by preventing P immobilization (e.g. Hafner *et al.*, 1993b).

2.4 Analysis of traditional and proposed technologies and need of decision support tools

2.4.1 Sustainability of proposed versus traditional technologies

Subbarao *et al.* (2000) studied the long-term effects of tillage, phosphorus fertilization and crop rotation on pearl millet productivity at Sadoré and found that the traditional system was more stable although it had the lowest yield. In another case study combining 13 alternative technologies including sole millet or intercropping, improved cultivars, P fertilizer application, tillage and rotation Subbarao *et al.* (2000) found again the traditional production system to be more stable. As the degree of intensification increased in the Sahel, the stability of the production system declines (Subbarao *et al.*, 1999). De Rouw (2004) found similar results regarding plant densities. They observed that conventional low density planting did not produce high yields as frequently as higher densities under favorable conditions. However, there was less crop failure under harsh conditions with low density sowing, although lower average grain yields were realized.

2.4.2 The Sahel: a complex agricultural research environment

Many authors have emphasized that the interpretation of experimental research is often difficult because the soils which have developed in coversand materials, although uniformly very sandy, exhibit a great spatial variability within distances as short as a few meters (Voortman *et al.*, 2004). The local soil variability leads to large variations among replications of experimental treatments. Moreover annual rainfall variability causes research results not to be consistent from year to year and there is a poor comparability of results across locations and climatic conditions (Schlecht *et al.*, 2006).

2.4.3 Level of adoption of proposed technologies and need for decision support tools

Research efforts have provided the foundation for extension in Sahelian countries (Reddy, 1988; Klaij *et al.*, 1994). In Niger, for example, extension has formulated a set of proposals : (i) higher plant densities were recommended as a means to achieve higher yields at low cost; however, significant increases in density should only be made in conjunction with additional nutrient input (Bationo *et al.*, 1992, 1990b); (ii) modest quantities of N and P should be applied next to individual hills for their most effective use; (iii) selected short cycle cultivars should replace the local landraces, especially if the rains are late. As a consequence, these proposals were tested further in suitable rainfall zones throughout Niger (INRAN, 1990) and were applied in many development projects (Ukkerman and Hama, 1995; De Rouw, 2004).

However, these recommendations have not been widely adopted. Selected cultivars, mineral fertilizers, and cropping practices such as higher stand density have been used by only a few farmers within the development projects and nowhere else (Abdoulaye and Lowenberg-Deboer, 2000). Fertilizer recommendations are often based on nutrient response trials limited to a few years and locations. Sometimes standard or 'blanket" recommendations are applied for whole agro-ecological regions or even the whole country (Vanlauwe and Giller, 2006). It is hard, in this sense, for extension services to match research findings to farmers local site conditions which may not be comparable to on-station or on-farm conditions found elsewhere. Recommendations need to be more flexible. In addition, the difference in priorities between researchers, who aim to improve yields in average years, and Sahelian farmers, who seek to reduce the frequency of crop failure, could explain the non-adoption of most innovations because the risks of yield losses were not reduced (De Rouw, 2004). Farmers are knowledgeable about, and practise soil fertility improvement technologies of rock phosphate application, crop residue and farm yard manure, mineral fertilizer and crop rotation to combat soil fertility decline. Their attitudes to and rationales behind adoption decisions are influenced by the availability of the technology and land use policies and available labour resources, food security concerns, perceived profitability, contribution to sustainability and access to information. Some of the factors are beyond farmers' control and require a broad and integrated effort from research, extension and government to promote the use of the fertility improvement technologies in the region (Enyong *et al.*, 1999).

Given the complexity and heterogeneity of the millet-based cropping systems in the Sahel, the situation undoubtedly calls for comprehensive, easy and low cost tools. DSTs such as numerical soil/crop simulation models could play a major role, helping in saving time and money from long years of field/station experiments and capitalizing on farmers' local knowledge and existing research findings.

2.5 State of the art of soil/crop modeling in semi-arid Africa

Soil/crop models will be shortly described. Experience with the use of such models in the Sahelian context will be presented, highlighting successes and shortcomings. Models are presented following chronological order of use in the crop yield modeling science. Statistical models have been used for yield prediction for several decades, water-balance models took up the challenge by tackling water requirement satisfaction in relation to crop production. More recently efforts were made to take into account processes related to plant nutrient interactions. Although potentially important, modeling of biotic stresses will no be discussed here.

2.5.1 Empirical-statistical models

This approach goes back to the 1930's and is the oldest form of crop modeling. Yield is predicted as a statistical function of observed key environmental characteristic averaged over part or all of the growing season (e.g. Thompson, 1986; Dourado-Neto *et al.*, 1998a,b). The statistical functions are usually developed by simple/multiple regression techniques (stepwise linear, ordinary least squares (OLS) and maximum likelihood estimation (ML)). These environmental characteristics are typically climate (precipitation, solar radiation and temperature, evapotranspiration averaged over the growing season or over specific periods) and soil (nutrient status, organic matter content, particle-size distribution). For example in the millet-based Sahelian system, millet grain yield has been explained as a function of N rate and annual or mid-season rainfall (Christianson *et al.*, 1990); N rate, plant density and rainfall during a particular crop phase (Bationo *et al.*, 1990b), N, P and /or K rates (Fussell *et al.*, 1987); N, P and K rates with other soil, terrain and management variables (Voortman and Brouwer, 2003). As with any empirical model, these models can only be applied in their original zone of calibration. Extrapolation to new conditions is not warranted. Although these models may have a role under particular circumstances, they have been largely replaced by models that are more or less dynamic, at least with respect to the soil water balance.

2.5.2 Water-balance (stress index models)

Given soil constraints to efficient water use, and the critical importance of available water to food security in semi-arid West Africa, considerable regional effort has been devoted to water balance studies and models. Dynamic water balance models simulate infiltration, runoff, drainage and evaporation from bare soil. Simple descriptions of crop canopy development permit calculation of transpiration. A stress index such as the time integral of the ratio of actual (i.e., soil- or root-limited) to potential evapotranspiration can be related empirically to reduction of growth and yield. The stress index approach (Doorenbos and Pruitt, 1977) is not fundamentally different from that used in dynamic process crop models. Taking canopy characteristics as an input rather than a dynamic state variable greatly simplifies the model but also does not permit to take into account feedback mechanisms, such as early-season water stress and later-season demand. Water balance - stress index models have been applied to a broader range of scales than process models. They are applied rather routinely in West African countries for agrometeorological and food security assessments. SARRA-based models (Système d'Analyse Régional des Risques Agroclimatiques-Habillé) typically and deterministically simulate attainable yields (water-limited under optimal soil fertility condition) at the field scale, but may also be stochastic and operate at variable temporal and spatial scales (Samba, 1998; Baron *et al.*, 1999). Extrapolation from plot to region is routinely done by the Centre Regional de Formation et d'Application en Agrométéorologie et Hydrologie Opérationnelle (AGRHYMET, Niamey) for agro-meteorological forecasting using the DHC system ("Diagnostic Hydrique des Cultures"), which includes SARRA as a component (Samba, 1998). A specific sub-model was developed for millet (SARRA-millet or SARRAH-mil) and was structured to enable such applications as well, but with greater physiological detail. It is frequently used by agronomists and agro-meteorologists working in the Sahel. It has been used for zoning and risk analyses (Affholder, 1997; Baron *et al.*, 1999; Sultan *et al.*, 2005b), to analyze the impact of regional climatic variability on millet yield (Sultan *et al.*, 2005a) and to predict agricultural plot yield based on Global Circulation Model output (Baron *et al.*, 2005).

2.5.3 Dynamic process models

Over the past 25 years, many individual modelers and collaborative groups have attempted to develop models that simulate the growth of crops, along with associated phenomena that influence crop growth such as water and solute movement in soils. Dynamic process models are then those which simulate through time (usually on a daily or sub-daily time step) the ecological and physiological processes of crop growth and development and its interaction with the environment. Experience has led to a distinction between mechanistic* models that try to capture our understanding of the mechanisms behind subsets of those processes with the primary objective to advance our understanding, and functional models that make useful simplifications so that data requirements and the robustness of predictions are appropriate for a rather broad range of practical applications (CLIMAG-WA, 2002). A short overview will be given for the five most promising and widely known ones (irrespective of age or importance): "School of de Wit" models, DSSAT, APSIM, STICS, Cropsyst. We will deliberately omit model scientific details because they have been adequately described in papers and books referenced below. Examples of applications in semi-arid Africa will be given and complemented with other applications in Africa in general because of the very few crop modeling works in the Sahel.

"School of de Wit" models The modeling group from Wageningen Agricultural University, The Netherlands - nicknamed the "School of de Wit" in honor of their early crop modeling pioneer - has taken a rather different approach than its successor models (Bouman *et al.*, 1996). Instead of developing comprehensive, general purpose models, they have emphasized application-dependent models, and have developed tools to facilitate rapid development of relatively simple models. Yet we can identify an evolving family of crop models that includes SUCROS, MACROS and WOFOST. A model for sorghum,

*Despite being qualified as "mechanistic", such models still have a large empirical component in their descriptions of sub-systems millet and maize with a tipping-bucket soil water balance model has been developed for use in the Soudano-Sahelian region (Bazi *et al.*, 1995).

DSSAT (CERES and CROPGRO) The decision support system for agrotechnology transfer DSSAT (Jones *et al.*, 2003) has been in use for the last 15 years by researchers worldwide. DSSAT is a product of the decade-long (1982-1993) IBSNAT (International Benchmark Sites Network for Agrotechnology Transfer) project. The basis for the new DSSAT cropping system model (CSM) design is a modular structure in which components separate along scientific discipline lines and are structured to allow easy replacement or addition of modules. It has one Soil module, a Crop Template module which can simulate different crops by defining species input files, an interface to add individual crop models if they have the same design and interface, a Weather module, and a module for dealing with competition for light and water among the soil, plants, and atmosphere. It is also designed for incorporation into various application packages, ranging from those that help researchers adapt and test the CSM to those that operate the DSSAT-CSM to simulate production over time and space for different purposes.

Within DSSAT, the relevant models are CERES, which includes the dryland cereal crops, and CROPGRO for grain legumes (Jones *et al.*, 2003). CERES and CROPGRO (grain legumes) differ considerably in their level of detail, degree of modularity and underlying physiological assumptions. Both CERES and CROPGRO models have undergone some testing and application in semi-arid West Africa (Table 2.4). Jagtap *et al.* (1999) describe decision applications in a more sub-humid environment in Nigeria. Thornton *et al.* (1997) developed a prototype GIS-based, real-time yield forecasting system for Burkina Faso that uses CERES-Millet and satellite-derived precipitation estimates combined with historic weather data series. CROPGRO-Peanut performed well in recent experiments in northern Benin (Adomou *et al.*, 2005) and Ghana (Naab *et al.*, 2004) when observed disease damage was properly accounted for. For an experiment at Tara, Niger, CERES-Millet substantially over predicted LAI, biomass, grain yield and soil water content (Fechter *et al.*, 1991). On the other hand, Naab *et al.* (2004) obtained good predictions of soil water contents and use in groundnut experiments in northern Ghana. Models included in DSSAT (including their predecessors) have been used in more regions and for a broader range of applications than any other family of crop models.

APSIM The Agricultural Production Systems Simulator APSIM (Keating *et al.*, 2003) is a modular modeling framework that has been developed by the Agricultural Production Systems Research Unit in Australia. APSIM was

Table 2.4. List of various types of applications of the DSSAT crop models in Africa and example references that describe these applications in detail.

Type of application	Crop (Climatic zone and country)	References
Crop management	Millet (semi-arid Niger), Maize (semi-arid Kenya), Maize (Rwanda)	Fechter *et al.* (1991); Fechter (1993); Mbabaliye and Wojtkowski (1994); Wafula (1995)
Fertilizer management	Maize (Dry and wet Nigeria), maize (Malawi)	Jagtap *et al.* (1999); Thornton *et al.* (1997)
Irrigation management	Wheat (Egypt), Wheat (Zimbabwe)	Kamel *et al.* (1995); Macrobert and Savage (1998)
Climate change and variability	Maize (Zimbabwe)	Muchena and Iglesias (1995); Phillips *et al.* (1998)
Risk analysis	Millet (Semi-arid Niger) ; Maize and pasture (Dryland southern Africa)	Bley *et al.* (1991); Jones and Thornton (2002)
Food security	Millet (Soudano-Sahelian and Semi-arid Burkina Faso); Maize (South-Africa)	Jagtap *et al.* (1999); Thornton *et al.* (1997); Dupisani (1987)

developed to simulate biophysical process in farming systems, in particular where there is interest in the economic and ecological outcomes of management practices in the face of climatic risk. It is a modular framework. Its modules include a diverse range of crops, pastures and trees, soil processes including water balance, N and P transformations, soil pH, erosion and a full range of management controls (manure, fertilizer, weeding, irrigation, etc). APSIM has been used in a broad range of applications, including support for on-farm decision making, farming systems design for production or resource management objectives, assessment of the value of seasonal climate forecasting, analysis of supply chain issues in agribusiness activities, development of waste management guidelines, risk assessment for government policy making and as a guide to research and education activity.

APSIM (Mccown *et al.*, 1996) implements a high degree of modularity of the various modules and processes. The initial motivation was to improve flexibility to model cropping systems and a wider range of soil and management processes. It was developed primarily for Australia's agricultural industry, but now supports a variety of applications in many parts of the world. As a result of a relatively high level of funding and scientific and development staffing, model development is more active for APSIM than for any of the other families of crop models. APSIM includes all of the relevant crops including millet.

In Africa APSIM applications were mainly reported in its eastern and

Table 2.5. List of various types of applications of the APSIM crop models in Africa and example references that describe these applications in detail.

Type of application	Crop, Climatic zone and country	References
Low input farming systems	Maize, grain legumes (Dry and wet Zimbabwe, Malawi)	Shamudzarira *et al.* (2000); Shamudzarira and Robertson (2002); Chivenge *et al.* (2004); Robertson *et al.* (2005)
N and P release from organic source	Maize (semi-arid and Wet Kenya)	Kinyangi *et al.* (2004); Micheni *et al.* (2004)
Spatially explicit soil fertility management	Sorghum (Semi-arid Ghana)	Kpongor (2007)

southern parts and many other validation studies are in progress in other regions (Table 2.5). APSIM has been used to measure maize responses to low rates of N fertilizer application from mineral fertilizer (Chivenge *et al.*, 2004; Kinyangi *et al.*, 2004) or/ and manure (Micheni *et al.*, 2004); and to quantify the risks and returns of alternative technology investment options in allocating scarce resources (labor, capital and land) to achieve whole-farm production goals (Shamudzarira *et al.*, 2000; Shamudzarira and Robertson, 2002). Robertson *et al.* (2005) reported the ability of the APSIM model to simulate maize response to previous green manure legume (*Mucuna pruriens*) and N fertilizer application in Malawi. The APSIM model was also successfully tested to reproduce maize response to various P fertilizer in Western Kenya (Kinyangi *et al.*, 2004). APSIM application in West-Africa remains limited (Table 2.5). Kpongor (2007) reported that APSIM was responsive to both organic and inorganic fertilizer applications in semi-arid Ghana and a spatially explicit application of the model highlighted the essential role of crop residues and inorganic fertilizer in influencing the temporal variability in sorghum grain production and hence the impact of farmers' management practices on food security.

STICS The 'Simulateur mulTIdisciplinaire pour les Cultures Standards' STICS (Brisson *et al.*, 2003) is a model that has been developed at INRA (France) since 1996. It simulates crop growth as well as soil water and nitrogen balances driven by daily climatic data. It calculates both agricultural variables (yield, input consumption) and environmental variables (water and nitrogen losses). From a conceptual point of view, STICS relies essentially on well-known relationships or on simplifications of existing models. One of the key elements of STICS is its adaptability to various crops. This is achieved by the use of generic parameters relevant for most crops and on options in the model formalization concerning both physiology and management that have to be chosen for each crop. All the users of the model form a group that participates in making the model and the software evolve, because STICS is not a fixed model but rather an interactive modeling platform. Folliard *et al.* (2004) compared modeling of sorghum response to photoperiod to related function implemented in STICS. To our knowledge there have been no application of this model in semi-arid areas.

CropSyst The Cropping Systems Simulation Model CropSyst (Stockle *et al.*, 2003; Bechini *et al.*, 2003) implements model modularity through an object-oriented structure. The result is a relatively user-friendly and flexible simulation environment. CropSyst is one of very few dynamic crop models that incorporates pest (aphid) population dynamics and damage. Its potential use for forecasting spatial distributions of millet yields was demonstrated for Burkina Faso (Badini *et al.*, 1997), but without experimental validation of predictions. It has recently been used for grassland productivity analysis and soil carbon in response to time-controlled rotational grazing in semi-arid Mali (Badini *et al.*, 2007)

2.6 Which soil-crop simulation models and how they may help overcome agricultural constraints in the Sahel?

The main disadvantages of mechanistic and dynamic models versus simple empirical models are their complexity, the high demand in data not often available and the limited use and accessibility to stakeholders. On the other hand the complex water-nutrient-genotype interaction governing crop growth and development limits the usefulness of empirical models only to an understanding or determination of the most meaningful variables that may explain yield in experiments. Predictability of empirical models in the Sahelian environment is low which makes them unsuitable for long term system analysis. Given the complexity and heterogeneity of Sahelian production systems, the use of dynamic modeling tools seems to be a prerequisite. The reason of limited data availability which leads to opt for simple models, often delays interest in needed data collection. A good option may be to start with the few cases with enough data (such as the ICRISAT Sahelian center) to show possibilities and importance of data use in decision support and to draw research and data collection institutions to what may be possibly done.

Regarding the mechanistic and dynamic models, APSIM and DSSAT stand in good place involving most of the constraints and benefiting from a long history of collaboration with the scientific community in the area (Table 2.6). But none of them provide a build-in option to explicitly account for soil spatial

Table 2.6. Comparison of crop-soil simulation models according to the main agronomic yield determinants and constraints in the Sahel

	APSIM	CERES/DSSAT	STICS / CropSyst	SARRAH
Water stress	SOILWAT cascading layer model	SOIL cascading layer model ('tipping bucket')	cascading layer model	cascading layer model
	APSWIM numerical solution of Richards' equation	–	Richards'equation (CropSyst)	–
Carbon assimilation	Carbon balance	Carbon balance	Carbon balance	Carbon balance
Nitrogen stress	SOIL N Balance mineralisation, (de)nitrification, immobilization, volatilisation	Soil N Balance mineralisation (de)nitrification, immobilization, volatilisation	Soil N Balance mineralisation (de)nitrification, immobilization, volatilisation	–
Phosphorus stress	Soil P available for other crops, under development for millet	Soil P	–	–
Crops	Individual crop modules (APSIM-millet, maize, etc) Extended work on the tillering characteristic of millet	Individual crop modules (CERES-millet, maize, etc)	Many crops	Millet
Fertility management	- SurfaceOM (previously Surface, Residue) - Fertilizer	- Residue (R. and other organic matter decomposition) - Fertilizer	Fertilizer and other organic matter	–
Spatial variability	–	–	–	–
Soil Acidity	–	–	–	–
Computer code availability and licence cost	Code available on internet, free, in transition to open source development	Code available, nominal fee even for academic use	Code not available, Free	Code not available, nominal fee
Collaboration with Sahelian scientists	Yes	Yes	–	Yes

variability. Nevertheless this shortcoming may be accounted for by multiple point-level simulations and /or GIS combination. Recently the APSIM model benefited from an extended work on millet module calibration and mainly on its tillering characteristic (Van Oosterom *et al.*, 2001a,b, 2002). The specific tillering capability of APSIM (based on millet cultivars from semi-arid India) opened the door and guidance for pioneering works of eco-physiological millet characterization in other semi-arid zones, such as the Sahel, which any other crop soil model may benefit from in the future.

Neither APSIM nor DSSAT have been properly validated in the Sahel. Prerequisites to their successful use in the Sahelian environment involve: (1) an extended characterization of Sahelian millet cultivars, (2) an in-depth evaluation of these crop-simulation models with respect to the main agricultural constraints in the area (water, N and P management, and the high variability in soil physical and chemical properties). Neither model is currently capable of dealing with P balance (relatively to millet), an important millet yield limiting factor in the Sahelian area. Efforts are being made to quickly overcome this shortcoming.

The use of numerical crop simulation models is complex, and hardware requirements and computation time are high and generally beyond the capability of technology-transfer specialists. The process of perfect decision support systems should evolve into simpler models such as meta-models that constitute an alternative to the use of complex numerical models.

Chapter 3

Effect of sowing date on the development and yield of seven Sahelian millet genotypes under non-limiting water and nutrient supply: experiment and modeling*

Abstract

The productivity of the Sahelian millet-based systems is still low despite the great wealth of research trials carried out to alleviate the soil fertility and climate constraints over the last 30 years. To save time and expense and better capitalize on past research trials, the use of decision support tools (DSTs) may be undoubtedly essential in the Sahelian environment, but DSTs suffer from not being veritably established due to the absence of thorough eco-physiological millet characterization for modeling. For this goal the effect of photoperiod and temperature were studied for seven Sahelian millet cultivars sown on four sowing dates from April to July 2005 in Sadoré, Niger, under non-limiting water and nutrient supply. The APSIM-millet model was tested for its ability to reproduce the experiment using physiological parameters derived from it. The study reveals that late sowing had a detrimental effect on most agronomic state variables (leaf number, LAI, stover and grain yield and components) but the extent of this effect was cultivar dependent. Photoperiod effect was observed only on one cultivar (the landrace Maewa). Temperature played a major role in the effect of sowing date on millet development and yield both in terms of amplitude (and independently of photoperiod) and accumulated degree days. The APSIM model could adequately reproduce the seven Sahelian millet genotypes' behavior in terms of phenology, development and yield after introducing the experimentally derived physiological parameters. Taking into account the measured difference in leaf dynamics between sowing dates (due to temperature amplitude) and cultivar was decisive in the successful modeling exercise. Our study succeeded in providing the, so far unavailable, genetic and

*Adapted from: Akponikpè P.B.I., Gérard B., Fatondji D., Clerget B., Van Oosterom E., Bielders C.L. Effect of sowing date on the development and yield of seven Sahelian millet genotypes under non-limiting water and nutrient supply: experiment and modeling. *To be submitted* eco-physiological parameters for seven Sahelian millet cultivars. These parameters, though tested only here within the APSIM model, may also be used within other dynamic crop simulation model and open the door for further modeling works in the area.

Keywords: Temperature, photoperiod, sowing date, model, millet, Sahel, APSIM

3.1 Introduction

Crop-soil simulation models are widely used to better understand and support decision making in agricultural systems (Gijsman *et al.*, 2002; Jones *et al.*, 2003; Keating *et al.*, 2003; Moeller *et al.*, 2007). The use of such decision support tools (DST) enables to save time and expense from field and station trials and capitalize upon past research outcomes. This is particularly true in the Sahelian environment where research trial results are highly site and year-specific due to high spatial variability in soil properties and high inter- and intra-annual rainfall variability. Hence, crop-soil models can help with the interpretation of experimental data and, after careful calibration and validation, can be used in a prospective way in conjunction with field data to draw recommendations better adapted to the risk-minimization strategies used by farmers in these environments.

So far except at the regional scale for yield forecasting purposes, the use of crop models for decision support in millet-based systems in the Sahel is very limited. This is because the complexity and heterogeneity of the system call for detailed and dynamic simulation models which must be parameterized and tested with respect to millet [*Pennisetum glaucum (L.) R.Br.*] water and nutrient responses but first and foremost with respect to the phenology and determinants of yield of the dominant cultivars found in the region. Indeed, farmers rely on multiple cultivars with variable length of growing cycle and sensitivity to photoperiodism as part of their risk management strategies. In addition, a number of improved cultivars have been introduced by national and international agricultural research organizations over the last decades, some of which potentially present an interest in famine mitigation strategies in case of late rains because of their short growth cycle (Ahmed *et al.*, 2000). Without cultivar-specific parameterization, risk management strategies relying on this diversity of crop responses cannot be properly evaluated using crop-soil simulation models. This is supported by recent preliminary modeling works using the APSIM model and its specific millet module (Keating *et al.*, 2003) under Nigerien climatic and fertility management conditions (Akponikpè *et al.*, 2006) . These works showed that the model based on initial parameterization from the Indian cultivars (Van Oosterom *et al.*, 2001a,b, 2002) failed to simulate correctly millet ontogeny of a Sahelian genotype (CIVT : Composite Inter-varietal de Tarna). Therefore, the characterization of Sahelian millet genotypes is a prerequisite for the successful application of crop-soil models in millet-based systems.

The first step towards this goal is the characterization of the most important cultivars under non-limiting water and nutrient conditions. Under such conditions, photoperiod, temperature and genotypes are the main factors that may influence the growth and yield. Temperature has long been recognized as the main environmental determinant of plant growth rate (Gregory, 1986; Shaykewich, 1995). Plant response to temperature can be summarized in terms of three cardinal temperatures: base (Tbase), optimum (Topt), and maximum (Tmax) temperatures which are commonly reported for many crops including millet (Hammer *et al.*, 1998; Birch *et al.*, 1998a,b). Plant activity increases slowly with temperature at values just above Tbase at which activity is zero. It then increases linearly with temperature in an intermediate range, and eventually continues to increase slowly as the temperature approaches Topt. At temperatures above Topt, activity is reduced as the temperature increases, and eventually ceases when Tmax is reached (Ong and Everard, 1979; Yan and Hunt, 1999). Specific studies regarding millet response to temperature corroborate the above described response. The most important contribution was provided through a suite of controlled environment glasshouse experiments (Monteith *et al.*, 1983). Temperature was shown to influence all aspect of millet growth and development, e.g., seedling emergence, leaf initiation and appearance (Ong, 1983a,b; Van Oosterom *et al.*, 2001b), tillering (Ong, 1984), light interception and dry matter production (Squire *et al.*, 1984; Squire, 1989a,b).

Regarding crop response to photoperiod, crop genotypes are classified photosensitive (or obligate short-day plants, referred to as short-day plants in the following) or non-photosensitive (facultative short-day) (Ong and Everard, 1979; Maiti and Bidinger, 1981; Birch *et al.*, 1998a,b). Previous works showed that short day (12h) photoperiods imposed on four short-day hybrid millet cultivars from India, grown in controlled environments, considerably shortened the time to anthesis and plant height and the final number of leaves produced (Ong and Everard, 1979). Carberry and Campbell (1985) observed on millet genotype BJ 104 at Hyderabad, India, that extended photoperiod increased time to panicle initiation and reduced grain yield at low plant population. Bacci *et al.* (1999) also found that the sowing date affected the emergence-earing duration independently of nitrogen application on the M9D3 millet cultivar in Mali but without referring to the underlying photoperiod effect. In Sahelian Niger, except for improved cultivars for which indicative cropping cycle durations are given, landraces are classified as either early, medium or late cultivars but no information is available about their photosensitivity.

In the Sahel, both photoperiod and temperature vary in regard to sowing date, the range of potential sowing dates being very wide (April to July) because rain onset is also very variable from one year to another (Sivakumar, 1990). Early sowing is associated to long day-lengths (photoperiods) and high air temperatures that may affect millet growth and production. In fact, photoperiods are long (13h12mn to 13h40mn) during the reasonable sowing period and decrease significantly only after the end of July. Temperatures are also high during the sowing period and decrease afterwards as the rainy season fully establishes itself. This variation of photoperiod and temperature as a function of sowing date in the Sahel was hypothesized to have a significant effect on growth and yield of Sahelian millet genotypes. The objectives of this paper were therefore to (1) study the effect of sowing date (associated with decreasing photoperiod and temperature) on millet phenology, growth and yield for 7 common millet genotypes in Sahelian Niger under non-limiting water and nutrient supply, (2) to experimentally derive the important cultivar-specific crop model parameters and (3) to test the performance of the APSIM-millet model to reproduce the cultivar-specific response to sowing dates under optimal water and nutrient supply conditions in the

Sahelian soil and climate environment.

3.2 Materials and methods

3.2.1 Experimental site

The experiment was conducted during the year 2005 at Sadoré, Niger (13°15'N, 2°17'E and 240 m of altitude) 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. The climate is typical of the southern edge of the Sahelian zone, with summer rainfall and high temperature throughout the year. The annual rainfall in Niamey is 545 mm and the average temperature is 29°C (Sivakumar *et al.*, 1993).

The soil is classified as sandy, siliceous, isohyperthermic psammentic Paleustalf with 91% sand, 5% silt and 4% clay in the A horizon, with a bulk density of about 1.65 Mg m-3 (West *et al.*, 1984), a pH(water) of 4.9, CEC of 1.3 cmol kg^{-1}, base saturation of 42%, organic carbon content of 0.2% and available phosphorus (Bray-P1) of 3 mg kg^{-1} (Hafner *et al.*, 1993b). Soil water content at field capacity is 0.09 to 0.10 m^3 m^{-3} (Klaij and Vachaud, 1992).

3.2.2 Experimental design and crop management

The experiment consisted in a completely randomized block design with two factors in three replications: (1) seven millet genotypes (Table 3.1) and (2) four sowing dates (S1 to S4) at one month interval (19 April, 19 May, 18 June and 19 July), covering the widest and reliable millet sowing period in the Sahel. Photoperiod at sowing were 13.17, 13.52, 13.69 and 13.58 hr for the first to the fourth sowing (Table 3.2). Photoperiod is civil daylength (daylight plus twilight) computed after (Alagarswamy and Ritchie, 1991). Individual plot size was 9 x 11 m (Figure 3.1a). A total of 60 kg N ha^{-1}, 12 kg P ha^{-1} and 9 kg K ha^{-1} were applied combining a basal dressing of Single Superphosphate (SSP) before sowing, hill placed NPK (15-15-15) at sowing and split application of urea approximately at tillering and flowering. Millet was sown at a density of 10000 hills ha^{-1} and thinned to 3 plants per hill between 15 to 20 days after emergence. Seven millet cultivars were studied: (1) four landraces (Ankoutes, Hainikirey, Maewa and Zongo) selected from the most commonly used by farmers in the three main agro-ecological zones of Niger (Fakara in the South-West, Maradi in the Southern center, and Zinder in the East) and (2) three representative improved cultivars (ICMV-IS-89305, CIVT and ZATIB) originating from research at ICRISAT or the National Agricultural Research Institute (INRA)(Table 3.1).

Supplemental irrigation was provided with a linear moving sprinkler system during dry spells in the rainy season (Figure 3.1a). Until the rainy season onset, irrigation requirements were estimated according to the pan evaporation rate of the previous week. On average 131 mm (rainfall: 84 mm and irrigation: 47 mm) of water was provided each month of the experiment.

Pest control was done regularly using Deltamethrin (Decis) and Dichlorvos. Bird

Table 3.1. Description of the millet genotypes used in the experiment. Name of the improved cultivars are intentionally written in capital letters.

Millet Genotype	Origin	Theoretical maturity	Source
Maewa	Ecotype from Madarounfa, Maradi, Niger 13.18N, 07.09E	late	Farmers
Zongo	Ecotype from Rwafin wada, Maradi, Niger 13.39N, 06.33E	early	Farmers
Ankoutes	Ecotype from Miria, Zinder, Niger 13.47N, 08.48E	early	Farmers
Hainikirey	Ecotype from Fakara, Margou, Niger 13.06N, 02.52E	medium	Farmers
ICMV-IS 89305	Breeding selection from 3-4HK B-78, Souna-3 and CIVT genotypes	early	ICRISAT-Niger
ZATIB	Breeding selection from Zanfarwa and Tchin-Bijini ecotypes	early	INRAN-Niger
CIVT	Breeding selection from P3 Kolo, HKN, Guerguera and Tamangagi genotypes	early	INRAN-Niger

Table 3.2. Photoperiod and average daily temperature shortly (0-20 DAS) after sowing. Values in brackets are standard deviation (sd).

		19 Apr.	19-May	18 Jun.	19 Jul.
Photoperiod (h)	Range	13.2 - 13.4	13.5 - 13.7	13.7 - 13.7	13.4 - 13.6
	Average(sd)	13.3(0.1)	13.6(0.0)	13.7(0.0)	13.5(0.1)
Temperature (°C)	Range	29.1 - 36.2	26.5 - 36.4	26.2 - 33.3	25.9 - 31
	Average(sd)	33.7(1.7)	32.8(2.9)	29.2(1.6)	28.5(1.4)

guard (human and scarecrow) was also done every day on plots at grain filling or maturity stages.

3.2.3 Measurements and analysis

The development phases from emergence to maturity were recorded on 2 rows of 10 hills per plot by counting daily the number of main shoots reaching the considered phase as defined by Maiti and Bidinger (1981). To compute the leaf area index (LAI), leaf dynamics on the main shoots and primary tillers was characterized weekly non destructively on 5 tagged plants (1 plant per hill) per plot. Each leaf was scored with a black permanent marking pen following its rank on the main shoot (Figure 3.1b). Primary tiller number index was added in case of tiller leaves. Each primary tiller was scored after the number of the leaf on the main shoot on which it appears. Number of visible, appeared (fully expanded) and senesced leaves from leaf 3 to flag leaf were recorded. Length (from leaf tip to ligule) and width of the last fully expanded leaf (on main shoot or primary tiller) were measured with a ruler and served to compute individual leaf area LA using the relation LA = Shape Factor x Length x Width. Shape factors were calibrated on 200 to 350 leaves for each millet cultivar (not shown here). Duration of development phases was expressed as thermal time (TT) calculated on an

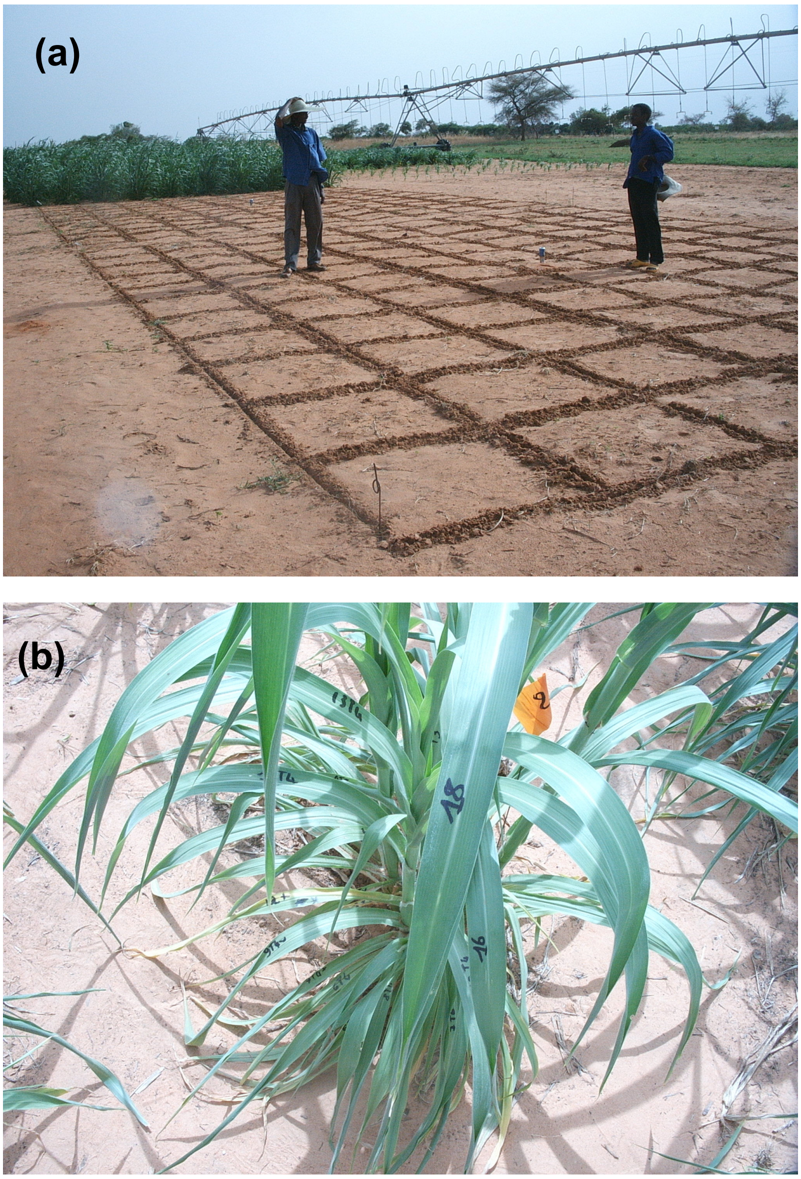

Figure 3.1. (a) Overview of the experiment on 17 June 2005: in the front is the preparation of the third sowing S3, in the back are plots of the first sowing S1 (high millet plants, 60 DAS), one plot of the second sowing S2 (short millet plants, 30 DAS) and the linear moving sprinkler irrigation system (far back); (b) leaf area dynamics monitoring by scoring (black permanent marking) individual leaves on tagged main shoot and its primary tillers.

hourly basis, using 10, 33 and 47°C as base, optimal and maximum temperatures, respectively, and assuming linear interpolation between these temperatures (Ong, 1983a; Van Oosterom *et al.*, 2001a). For this purpose, air temperature at 2 m aboveground was measured hourly and stored in a datalogger (Campbell CR10). The time for leaf appearance or fully expanded (TLA) was estimated, from the change in the average total leaf number (TLN) as a function of thermal time, for each cultivar and sowing date.

Final harvest was done on 20 m^2. Counts were done for number of productive and unproductive shoots/tillers. Biomass yield was split into straw and grain. 1000 grain weight was determined based on ten 1000-grain samples per genotype and per plot. Grain yield Y was expressed in terms of its components as: Y (kg ha^{-1}) = D x NPP x NGH x GW, where D is the planting density (hill ha^{-1}), NPP the number of productive panicles per hill (panicle $hill^{-1}$), NGH the number of grains per panicle or head (grain $panicle^{-1}$) and GW the individual grain mass (kg $grain^{-1}$). All results were submitted to analysis of variance in Genstat 6 (Laws Agricultual Trust, 2002). Differences between treatments were considered at error probabilities < 0.05.

3.2.4 APSIM model parameterization and simulation

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). Three modules - a specific crop module (APSIM-millet 3.6, full description in Appendix), a soil water module (Soilwat2), the soil nitrogen module (Soiln2) - were linked within APSIM to simulate the cases described in this paper. Input data required by the APSIM model are related to the climate, crop genetic and soil characteristics, and management (sowing, fertilizer application, etc.).

Climate and soil data Climate data (daily rainfall, minimum and maximum temperatures, radiation) were obtained from an automatic meteorological station located at the experimental site. Irrigation amounts were added to daily rainfall in the meteorological data file. Soil chemical and physical parameterization was based on literature and calibration from previous crop model (CERES, APSIM) validation works (Fechter *et al.*, 1991; Akponikpè *et al.*, 2006, 2007).

Phenology The parameterization of the studied cultivars was based on the computed thermal times derived from this experiment (Table 3.4). Two approaches of parameterization were implemented:

- approach I was based on identical leaf dynamics across cultivars and sowing dates as reported for Indian millet cultivars at Patancheru and proposed as default in the APSIM-model (Van Oosterom *et al.*, 2001a). The corresponding thermal time value for leaf initiation or plastochron (TLI) was 27.2 °C day per leaf and the thermal time for leaf appearance or phyllochron (TLA) was 36.4 °C day per leaf.
- approach II takes into account the differences in leaf dynamics across cultivars and sowing dates, as derived from the present experiment. As only TLA was

measured, we hypothesized that the TLI/TLA ratio was identical for all cultivars and equal to that published for Indian genotypes (TLI/TLA = 0.75) (Table 3.4).

Except for TLI and TLA in approach I, all thermal times were computed based on experimental observations from the starting till the ending day of each phenological phase and were averaged over the four sowing dates for each cultivar (Table 3.4). Only the thermal time from emergence to end juvenile (T_EM_EJ) could not be computed from start-end phenology observations. We estimated it as follows:

$$T\_EM\_EJ = T\_PI - T\_EJ\_PI \tag{3.1}$$

$$T\_PI = TLI \times (TLN - 4) \tag{3.2}$$

$$T\_EJ\_PI = PPS \times (APP - BPP) \tag{3.3}$$

where T_PI is the time to panicle initiation, T_EJ_PI the time from end juvenile to panicle initiation, TLN the total leaf number, PPS the photoperiod sensitivity (default APSIM value of 112 °C days h^{-1}), BPP the base photoperiod = 12.9 h. APP is the actual photoperiod, which is the average photoperiod calculated over the period from sowing date to PI, estimated at 20 days. So four values of T_EM_EJ (one per sowing date) were obtained and the average for each cultivar was input into the model for simulation.

Leaf area and tiller number In APSIM-millet, individual leaf area of any leaf is calculated on the basis of its position and the area of the largest leaf y0 (Van Oosterom *et al.*, 2001b). y0 is a linear function of the total leaf number (TLN) on an axis and is modelled as:

$$y0 = y0\_const + y0\_slope \times TLN \tag{3.4}$$

where y0_const and y0_slope are genotype-dependent parameters. They were derived for each cultivar from measurements on 50 to 60 main shoots (Figure 3.2, Table 3.3). For any given cultivar, the same relation was used for tillers as for the main shoot. Tiller numbers were approximated to the closest natural number of the observed NPP as a function of sowing date (Table 3.3).

Grain yield The maximum number of grains per head (head_grain_no_max) of each cultivar was considered as the maximum observed over the four sowing dates of the experiment. Because grain growth rate was not measured, it was adjusted (identical for all cultivars) to match observations.

Model evaluation Graphical and statistical evaluation criteria were used. The root mean square error RMSE, the square of the correlation coefficient R^2, and the model efficiency EF were computed after Loague and Green (1991) for individual treatments

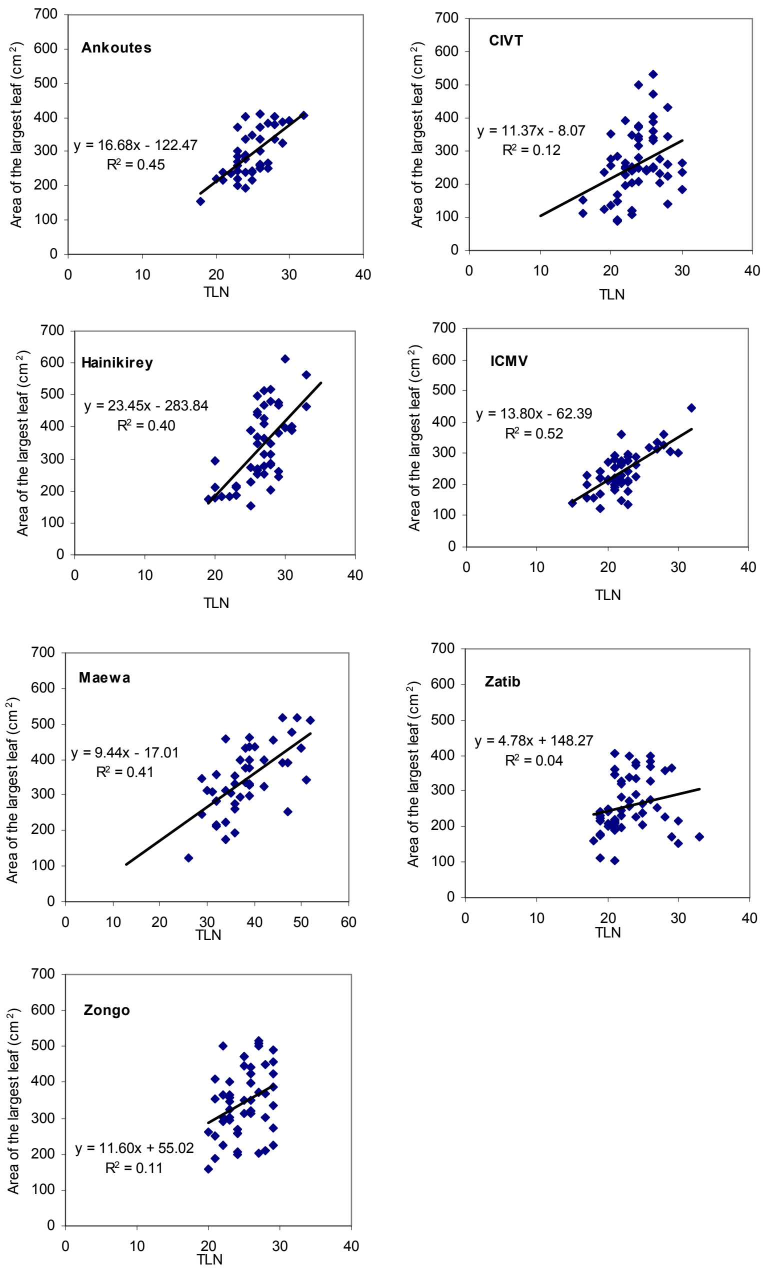

Figure 3.2. Linear regression between the area of the largest leaf (y0) and the total leaf number (TLN) on an axis for seven millet cultivars under non-limiting water and nutrient supply conditions and for four sowing dates in 2005 at Sadoré, Niger.

Table 3.3. Effect of millet cultivar and sowing date on maximum leaf area (LAImax), number of productive panicle per hill (NPP), the number of grains per head (NGH), 1000-grain weight, straw and grain yield for seven genotypes grown under non-limiting water and nutrient supply conditions in 2005 at Sadoré, Niger.

Cultivar	LAImax (m^2 m^{-2})	NPP (-)	NGH (-)	Grain weight (g/10^3 grains)	Yield (kg ha^{-1}) Straw	Yield (kg ha^{-1}) Grain
Ankoutes	1.6	3.3	3406	9.4	4273	990
CIVT	0.9	4.8	4293	7.6	5141	1569
Hainikirey	2.4	3.5	4338	8.5	4490	1265
ICMV-IS89305	1.2	4.7	4138	8.8	4023	1684
Maewa	3.5	4.3	3883	9.4	7985	1581
ZATIB	1.3	4.1	4224	8.7	4115	1541
Zongo	2.0	3.2	3815	8.4	4504	1071
Prob.	<.001	0.005	ns	<.001	0.004	0.012
s.e.d	0.3	0.5	357	0.4	1042	223
Sowing 19 apr.	3.3	4.9	4721	9.0	8426	1901
19 may	2.3	4.6	4533	8.3	6497	1683
18 jun.	1.0	3.1	3909	8.8	2563	1106
19 jul.	0.9	3.3	2893	8.7	2246	854
Prob.	<.001	<.001	<.001	ns	<.001	<.001
s.e.d	0.3	0.4	270	0.3	786	169
CV (%)	44.8	30.4	21.8	11.9	51.7	39.4

ns: not significant

Table 3.4. Genetic parameters of seven Sahelian millet genotypes sown on four dates under non-limiting water and nutrient supply conditions in 2005 at Sadoré, Niger.

Parameters	Units	Sowing	Cultivars						
			Ankou-tes	CIVT	Haini-kirey	ICMV-IS	Maewa	ZATIB	Zongo
Phenology									
leaf_app_rate2 (TLA)	°C day per Leaf	1	45	49	49	52	71	54	54
		2	45	50	42	51	60	48	55
		3	53	62	52	62	59	58	58
		4	64	66	57	59	47	62	61
tt_emerg_to_endjuv [a]	°C days	All	737	753	796	726	1528	698	828
pp_endjuv_to_init	°C days h^{-1}	All	112	112	112	112	112 [b]	112	112
tt_flower_to_maturity	°C days	All	400	380	400	400	400	400	400
tt_flag_to_flower	°C days	All	115	115	150	130	120	120	170
tt_flower_to_start_grain	°C days	All	112	112	112	112	112	112	112
Leaf area (main shoot)[c]									
y0_const	mm^2	All	-12247	-807	-28384	-6239	-1700	14827	5502
y0_slope	mm^2 per leaf	All	1668	1137	2345	1380	944	478	1160
Grain yield									
head_grain_no_max	grain $head^{-1}$	All	5500	5500	5500	5500	5500	5500	5500
grain_gth_rate	mg $grain^{-1}$ day^{-1}	All	0.7	0.7	0.7	0.7	0.7	0.7	0.7

[a] 100 + (n-1) x 10 °C day were subtracted for tiller number n to account for their earliness compared to the main shoot.

[b] Maewa was considered as non-photosensitive for the last sowing

[c] y0 = y0_const + y0_slope x TLN, where y0 and TLN are, respectively, the area of the largest leaf and the total leaf number on an axis. For any given cultivar, the same relation was used for tillers as for the main shoot.

for LAI throughout the growing period and for all grouped treatments for final biomass and grain yield.

Root Mean Square Error (RMSE),

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(S_i - O_i)^2} \tag{3.5}$$

The square of the linear correlation coefficient (0≤$R^2 \leq 1$),

$$R^2 = \frac{\left[\sum_{i=1}^{n}(O_i - \bar{O})(S_i - \bar{S})\right]^2}{\sum_{i=1}^{n}(O_i - \bar{O})^2 \sum_{i=1}^{n}(S_i - \bar{S})^2} \tag{3.6}$$

The Modeling Efficiency (EF≤ 1),

$$EF = 1 - \frac{\sum_{i=1}^{n}(S_i - O_i)^2}{\sum_{i=1}^{n}(O_i - \bar{O})^2} \tag{3.7}$$

where S_i and O_i are the simulated and the observed values respectively, n the number of observations, and $\bar{S}$ and $\bar{O}$ the mean of the simulated and observed values respectively. It is expected for a good simulation to have values of RMSE, R^2 and EF as close as possible to 0, 1 and 1, respectively.

3.3 Results

3.3.1 Duration from emergence to flowering

The time from emergence to flowering (T_EM_FL) was significantly different between sowing dates (p = 0.009). The sowing date effect was only observed for Maewa (sowing x cultivar interaction, p = 0.009) for which late sowing resulted in diminished T_EM_FL from 3014 (170 days) to 1621 °C day (92 days) from sowing 1 to 4 (s.e.d = 39 °C day or 2 days). Difference between cultivars was also significant ($p < 0.001$, Figure 3.3). Excluding Maewa, the average T_EM_FL over all sowing dates was 1380 (78), 1270 (71), 1491 (84), 1184 (66), 1188 (67), 1337 °C day (75 days) for Ankoutes, CIVT, Hainikirey, ICMV-IS89305, ZATIB and Zongo, respectively (s.e.d = 51°C day or 3 day).

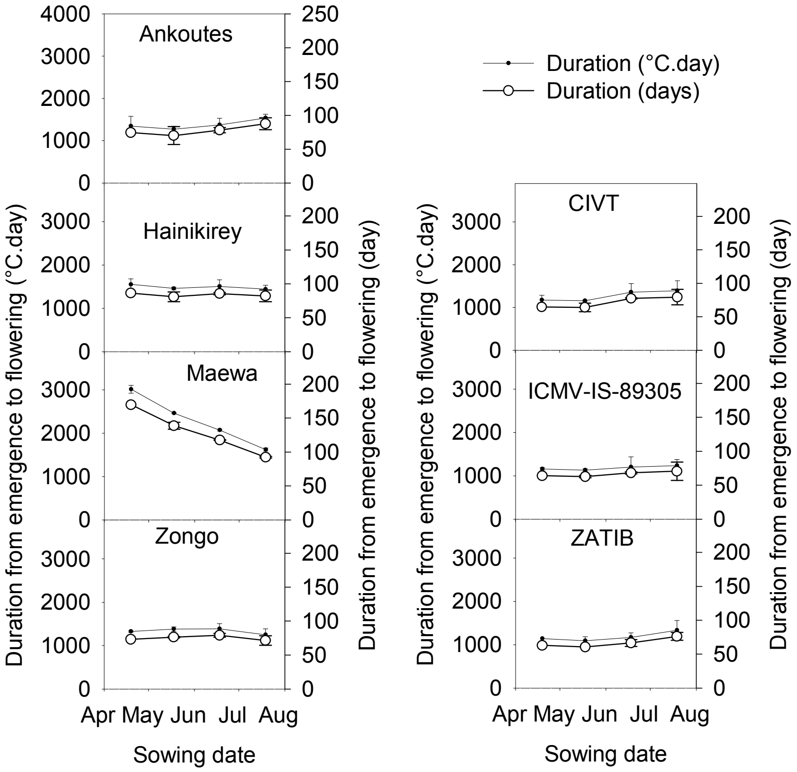

Figure 3.3. Duration from emergence to flowering (T_EM_FL) for seven millet cultivars under non-limiting water and nutrient supply conditions and for four sowing dates in 2005 at Sadoré, Niger. Error bars denote standard deviation of observed means, n=3

3.3.2 Total leaf number (TLN), time for leaf appearance (TLA) and leaf area index (LAI)

Total leaf number (TLN) on the main shoot was significantly different across cultivar and sowing date ($p < 0.001$). On average the landraces showed a higher leaf number (39, 27, 25 and 25, respectively for Maewa, Hainikirey, Zongo and Ankoutes) than the improved cultivars (22 leaves, s.e.d = 1.3 leaves). On average over all varieties, late sowing S4 resulted in 7 leaves less than the early sowing S1 which produced an average of 30 leaves for all cultivars (s.e.d = 1.0 leaf) (Figure 3.4a). However, there was a significant interaction between sowing date and cultivar (p = 0.005) because the decrease in the number of leaves from S1 to S4 was more important with landraces Maewa (20 leaves), Hainikirey, Zongo and Ankoutes (6 to 8) compared to the three improved cultivars (2 leaves, s.e.d = 2.7 leaves). The time for leaf appearance (TLA), estimated from the change in the average TLN as a function of thermal time was steady for each cultivar at any given sowing date. TLA was different across cultivars and sowing dates. TLA across cultivars ranged from 45 to 71 °C day per leaf for the first sowing and from 47 to 66 °C day per leaf during S4 (Figure 3.4b). TLA tended to increase from sowing 1 to 4 for all cultivars except Maewa for which it decreased.

Maximum leaf area (LAImax) was significantly different between cultivars ($p < 0.001$) and sowing dates ($p < 0.001$). On average the landraces (Maewa, Hainikirey, Zongo, Ankoutes) had a higher LAI than the improved cultivars (ZATIB, ICMV-IS89305 and CIVT) (s.e.d = 0.3 m^2 m^{-2}, Table 3.3). On average LAI decreased from 3.2 for early sowing to 0.9 m^2 m^{-2} for late sowing (s.e.d = 0.3 m^2 m^{-2}, Table 3.3). Intra-cultivar variability was higher for landraces compared to improved cultivars (not shown). No interaction was observed.

3.3.3 Straw yield

Straw yield was significantly different between cultivars (p = 0.004). The landrace Maewa produced the highest straw yield of 7985 kg ha^{-1} followed by the improved cultivar CIVT (5145 kg ha^{-1}) compared to the remaining cultivars (4200 kg ha^{-1}) (Table 3.3). Late sowing resulted in decreased straw yield from 8426 to 2246 kg ha^{-1} from sowing 1 to 4 ($p < 0.001$, Table 3.3). No interaction was observed.

3.3.4 Grain yield and components

Grain yield Cultivar effect was significant for grain yield (p = 0.012). The improved cultivars CIVT, ICMV-IS89305 and ZATIB as well as landrace Maewa produced higher grain yield than the landraces Ankoutes, Hainikirey and Zongo (Table 3.3). Grain yield significantly decreased from sowing 1 to 4 ($p < 0.001$, Table 3.3). No interaction was observed.

Grain yield components Thousand grain weight was only significantly affected by cultivar ($p < 0.001$) whereas the number of grains per head (NGH) was only affected by sowing date ($p < 0.001$). The landraces Ankoutes and Maewa showed the highest 1000-grain weight (9.4 g, Table 3.3) followed by Hainikirey, ICMV-IS89305,

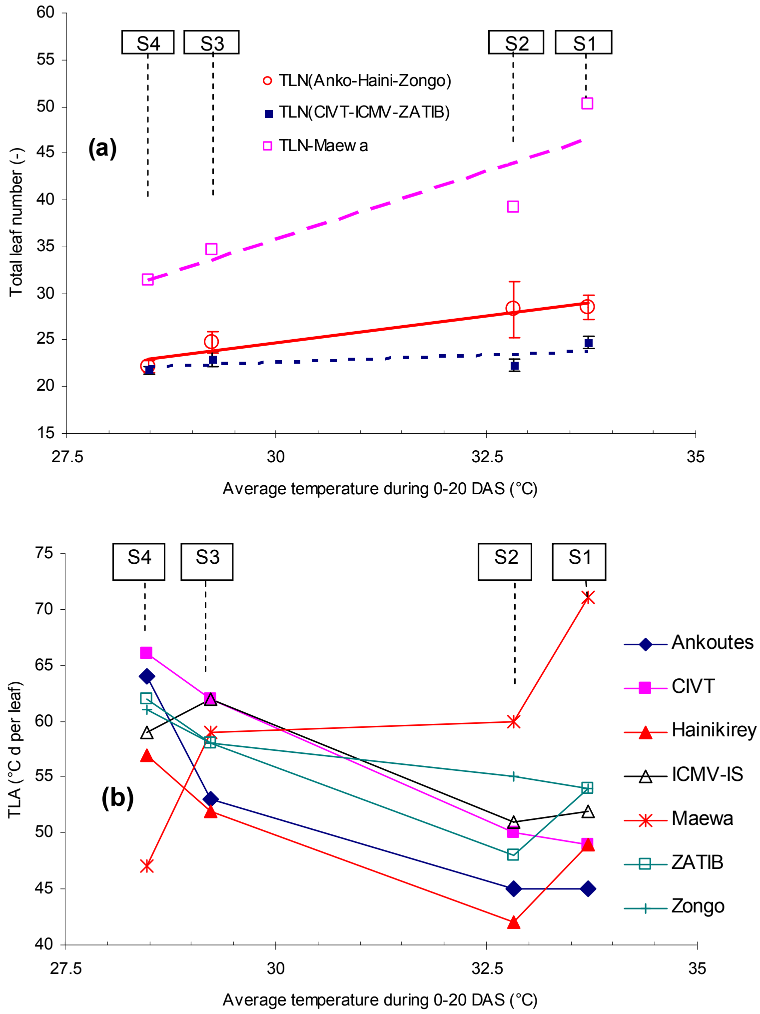

Figure 3.4. (a) Effect of temperature (sowing date) on total leaf number (TLN), and (b) temperature x cultivar effect on the time for leaf appearance (TLA) of seven Sahelian millet genotypes under non-limiting water and nutrient supply conditions in 2005 at Sadoré, Niger. Vertical bars denote standard deviation.

Table 3.5. RMSE from observed and simulated leaf area index of seven genotypes sown on four dates under non-limiting water and nutrient supply conditions in 2005 at Sadoré, Niger. Values in brackets denote the observed maximum LAI (LAImax).

	RMSE (LAImax) [m^2 m^{-2}]				
	S1	S2	S3	S4	Average
Ankoutes	0.3 (2.6)	0.2 (2.3)	0.2 (0.5)	0.1 (0.5)	0.2 (1.5)
CIVT	0.8 (1.8)	1.4 (0.9)	0.1 (0.4)	0.3 (0.5)	0.7 (0.9)
Hainikirey	0.7 (4.3)	0.5 (3.4)	0.6 (0.9)	0.4 (0.7)	0.6 (2.3)
ICMV-IS-89305	0.3 (2.1)	1.0 (1.0)	0.1 (0.6)	0.1 (0.4)	0.4 (1.1)
Maewa	-	-	-	0.2 (1.7)	0.2 (1.7)
ZATIB	0.3 (2.2)	0.4 (1.5)	0.2 (0.8)	0.1 (0.5)	0.2 (1.2)
Zongo	0.7 (3)	0.5 (2)	0.2 (1.1)	0.5 (1.4)	0.5 (1.9)

ZATIB and Zongo (around 8.5 g per 1000 grains). The improved cultivar CIVT had the lowest grain weight (7.6 g per 1000 grains) (s.e.d = 0.4 g per 1000 grains, Table 3.3). The number of grains per head was similar for sowing 1 and 2 (around 4600) but decreased to 3900 and 2800 for sowing 3 and 4, respectively (s.e.d = 270, Table 3.3). A slight sowing x cultivar interaction was observed for 1000-grain weight and the number of grains per head ($p = 0.040$ and 0.044 respectively). The number of grains per head of Maewa tended to be constant, whereas its grain mass increased with delayed sowing contrarily to the remaining cultivars (not shown). The number of productive panicles per hill was significantly affected by both cultivar ($p = 0.005$) and sowing date ($p < 0.001$). The improved cultivars CIVT (4.8), ICMV-IS89305 (4.7) and ZATIB (4.1) and the landrace Maewa (4.3) had the highest number of productive panicles per hill (NPP) compared to the other landraces Ankoutes, Hainikirey, and Zongo (< 3.5) (s.e.d = 0.5, Table 3.3). S1 and S2 had higher NPP (above 4.5) than S3 and S4 (less than 3.3) (s.e.d = 0.4, Table 3.3, Figure 3.4a).

3.3.5 Simulations with APSIM

Phenology The APSIM model was not able, in both approaches I and II, to reproduce satisfactorily the high photoperiod sensitivity of the Maewa cultivar. In fact, the model consistently ended up in exaggeratedly high simulated leaf numbers. The six remaining cultivars could be simulated properly because they were not photosensitive. For late sowing (S4), Maewa could also be adequately simulated because this sowing occurs when the photoperiod decreased under the critical value of 12.9 h. Hence, at S4, Maewa behaved like a non-photosensitive cultivar. In approach I, for which the parameters of leaf dynamics are considered the same across cultivars and sowing dates, the model underestimated the duration from sowing to maturity (DSM) and there was little difference between cultivars and sowing dates contrary to observation during the experiment (RMSE for DSM was 15 days, Figure 3.5a). In approach II, accounting for differences in leaf dynamics reproduced satisfactorily the observed differences between cultivars. In approach II the RMSE for DSM was 11 days. R^2 and EF were 0.47 and 0.91, respectively.

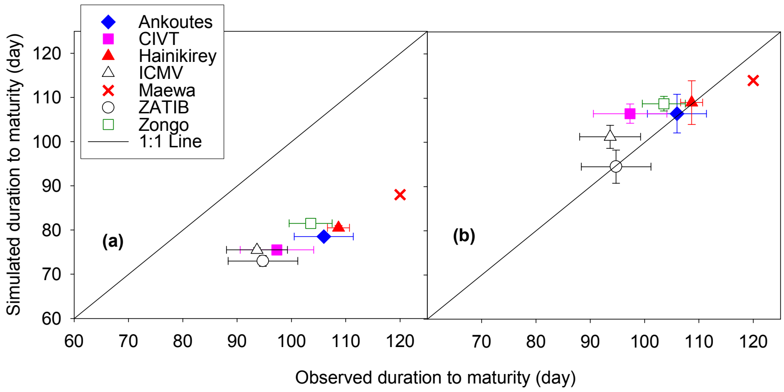

Figure 3.5. Averaged observed and simulated number of days to maturity in approach I (a) and II (b) of seven Sahelian millet genotypes sown in four dates under non-limiting water and nutrient supply conditions in 2005 at Sadoré, Niger. As no trend was observed with respect to the four sowing dates (Maewa was simulated only for the last date), average values over all sowing dates are reported. Error bars denote standard deviation.

Leaf number and leaf area index (LAI) As for DSM, there was little difference in TLN across cultivars in approach I (RMSE = 2.5 leaves, R^2= 0.26 and EF = 0.87, Figure 3.6a). There was also hardly any effect of sowing date. In approach II, simulated TLN covered a wider range and better reproduced the observed difference between cultivars and sowing dates (RMSE = 1.9 leaves, R^2 = 0.55 and EF = 0.92, Figure 3.6b). The observed decrease in TLN for later sowing was also well simulated (not shown). Because of poor phenology simulation, the model evolution of the leaf area index (LAI) during the growing season is not presented for approach I. For approach II, the performance of the APSIM model in reproducing the observed LAI varied according to the cultivar and sowing date. LAI in S1 and S2 were well simulated for Ankoutes, ICMV-IS 89305 and ZATIB, those of Hainikirey and Zongo were under-estimated whereas those of CIVT were over-estimated close to the maximum (Figure 3.7, Figure 3.8, Table 3.5). LAI simulations of S3 and S4 in approach II were satisfactory for all cultivars. Combining all cultivars, sowing dates and measurements the RMSE of the LAI was 0.52 m^3 m^{-3} (with an overall average of 0.79 m^3 m^{-3}), R^2 and EF were 0.64 and 0.59 respectively (Figure 3.9). For every cultivar the observed decreasing trend of LAI with respect to sowing dates was also well simulated.

Biomass and grain yield Biomass yield: RMSE was 2231 kg ha^{-1} (35% of global average across all cultivars and sowing dates). R2 and EF was 0.75 and EF was 0.65, respectively. The model reproduced satisfactorily the observed differences between cultivars (Figure 3.10a). The observed decreasing trend of yield with respect to sowing dates was in general also well simulated (Figure 3.10b), except for S1 which tended to be underestimated.

Grain yield: The model performed better in terms of grain yield than for total biomass. RMSE was 302 kg ha^{-1} (22% of global average across all cultivars and sowing dates). R^2 was 0.88 and EF was 0.75. The model reproduced well the observed

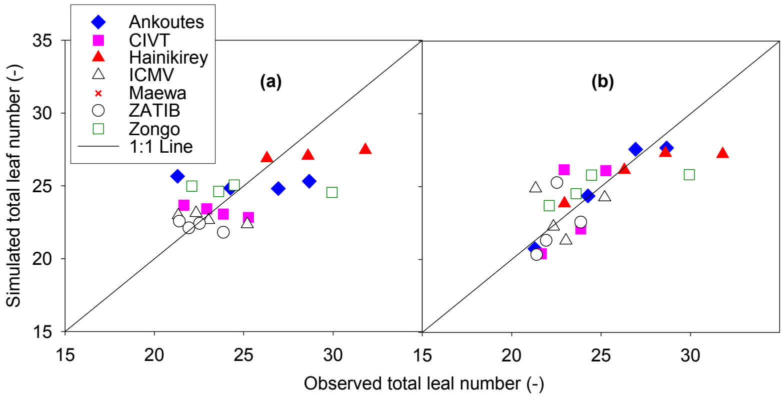

Figure 3.6. Observed and simulated total leaf number TLN in approach I (a) and II (b) of seven Sahelian millet genotypes sown in four dates under non-limiting water and nutrient supply conditions in 2005 at Sadoré, Niger.

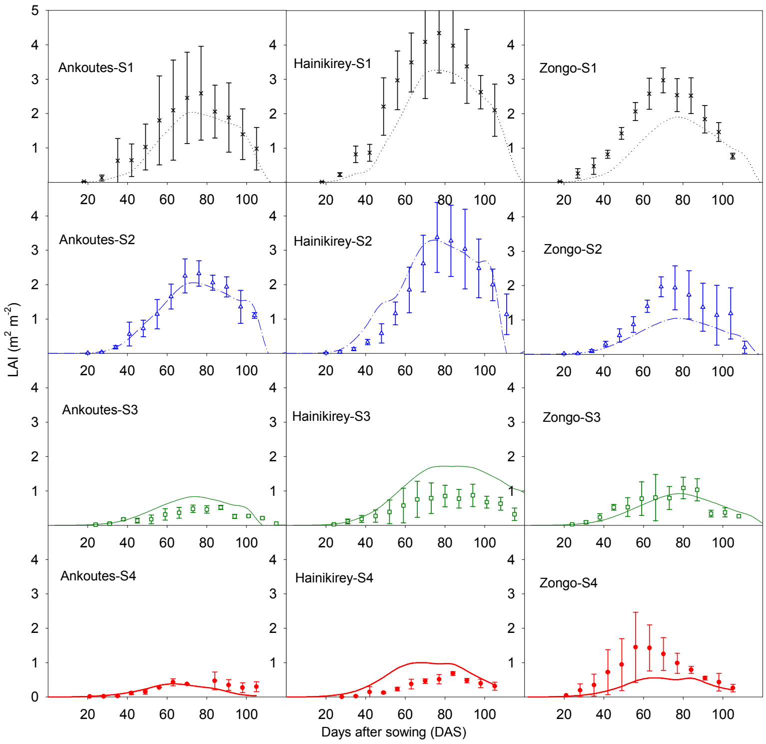

Figure 3.7. Observed (dots) and simulated (lines) leaf area index (LAI) of three Sahelian millet landraces sown in four dates (S1 to S4) under non-limiting water and nutrient supply conditions in 2005 at Sadoré, Niger. Error bars denotes standard deviation.

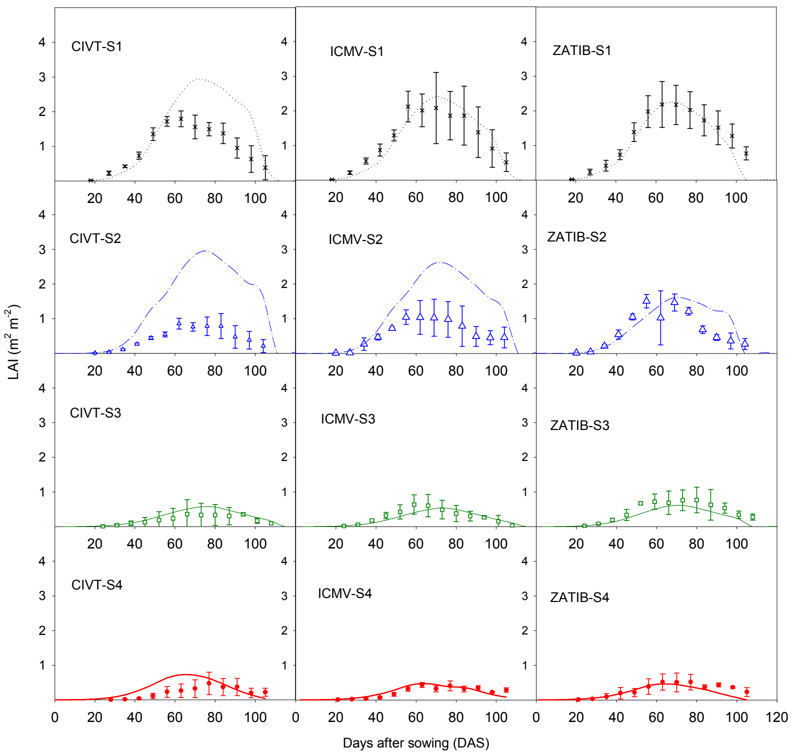

Figure 3.8. Observed (dots) and simulated (lines) leaf area index (LAI) of three improved Sahelian millet genotypes sown on four dates (S1 to S4) under non-limiting water and nutrient supply conditions in 2005 at Sadoré, Niger. Error bars denotes standard deviation.

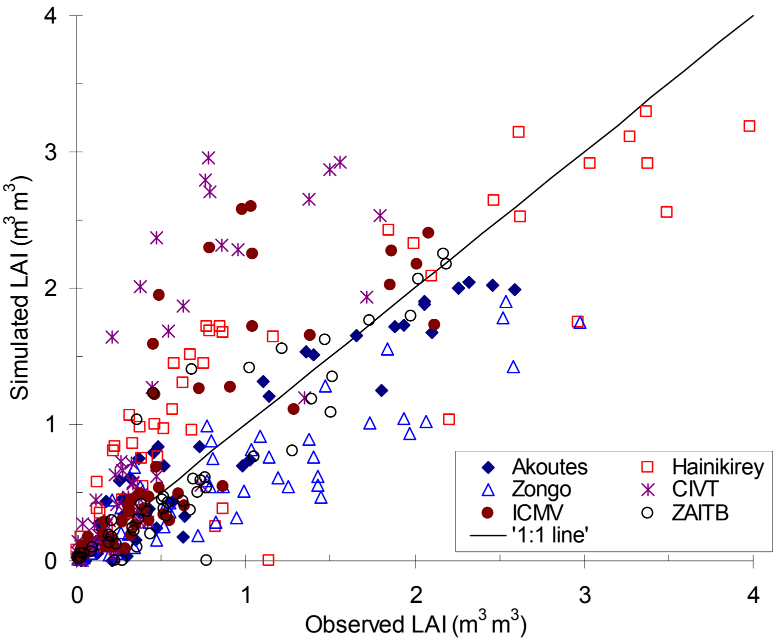

Figure 3.9. Comparison of the observed and the simulated leaf area index (LAI) of all the cultivars combining the measurements of the four sowing dates (except for the cases of Maewa in S1, S2 and S3) under non-limiting water and nutrient supply conditions in 2005 at Sadoré, Niger.

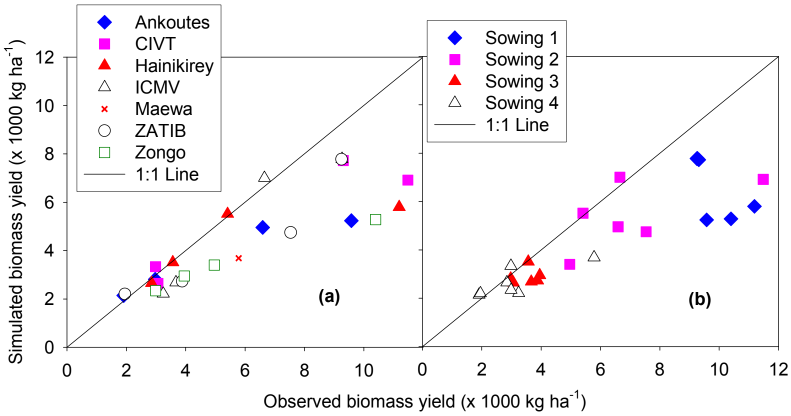

Figure 3.10. Observed and simulated biomass yield of seven Sahelian millet genotypes (a) sown on four dates (b) under non-limiting water and nutrient supply conditions in 2005 at Sadoré, Niger.

differences between cultivars (Figure 3.11a). The observed decreasing trend of yield with respect to sowing dates was also well simulated (Figure 3.11b).

3.4 Discussions

The objective of this paper was to characterize the phenology, growth and yield parameters of 7 common millet cultivars in Sahelian Niger. The temperature and photoperiod dependence of these processes was assessed through the effect of sowing date under non-limiting water and nutrient supply conditions. The ability of the APSIM model to reproduce the observed growth and yield using parameters directly derived from field measurements was also evaluated.

3.4.1 Millet development and yield

Only one studied cultivar, Maewa, was very photosensitive contrary to the other landraces and all the improved cultivars. It is well known that improved cultivars are generally early maturing and have stable crop duration due to intentionally reduced photosensitivity (Dingkuhn *et al.*, 2006). Improved cultivars used in this study (CIVT, ICMV-IS89305 and ZATIB) were derived from short cycle landraces such as Hainikirey-Bengou (HKB), Guerguera and Tamangagi, among others. This study confirms the absence of photosensitivity of the studied improved cultivars. For landraces, the degree of photoperiod sensitivity was a priori unknown because of lack of information. Our results reveal that the terms ’short’ and ’long’ cycle landraces may be misleading depending on the degree of photosensitivity of the cultivar. For example, if Maewa is sown late, it will resemble a short cycle landrace. When no information regarding photoperiod sensitivity is available, the characterization of phenology, growth and yield of a cultivar on the basis of a single sowing date may also lead to

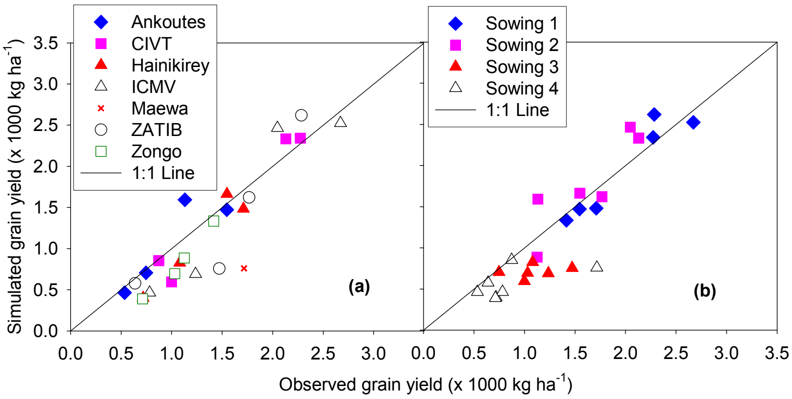

Figure 3.11. Observed and simulated grain yield of seven Sahelian millet genotypes (a) sown on four dates (b) under non-limiting water and nutrient supply conditions in 2005 at Sadoré, Niger.

erroneous results in case crop growth modeling is applied for sowing dates different from those that served for the characterization.

The study showed that landraces produced more leaves (TLN) and higher LAI and straw yield whereas improved cultivars produced higher grain yield except for cultivar Maewa. This difference in cultivar could be explained by the greater NPP and 1000-grain weight observed in improved cultivar and Maewa (Table 3.3). Improved cultivars have a higher harvest index, because priority has generally been given to grain production as opposed to other harvestable products. Stems or green foliage have multiple uses in traditional systems (Dingkuhn *et al.*, 2006) which explain farmer's attachment to landraces.

Late sowing resulted in decreased TLN, LAI, straw and grain yield and the number of grains per head was similar for sowing 1 and 2 but decreased significantly for sowing 3 and 4. Reddy and Visser (1993) studied the photosensitive landrace Somno and the non-photosensitive HKB in Bengou, Niger over 6 sowing dates during the 1986 and 1987 rainy seasons (no irrigation) following the application of 45 N ha^{-1} + 9 kg P ha^{-1} and obtained similar results of adverse impact of late sowing on straw and grain yields, although Somno grain yield was more stable. Three hypotheses may explain the detrimental effect of late sowing date on the above millet growth variables: (1) a better N nutrition for early sowing due to the contribution of the nitrogen flush, (2) temperature and (3) temperature x photoperiod effects. The nitrogen flush, though never scientifically proved in the area, is supposed to result from the rapid mineralization of organic matter upon first soil wetting after a long dry season. As irrigation started on the same date (April 19) on all treatments irrespective of sowing date, the nitrogen flush may have benefited early sown millet whereas for the later sown millet, leaching of N may have kept it out of reach of the growing roots. Coaldrake (1985) showed for pearl millet cultivar MX001 that the nitrogen supply affected the total leaf area of the main stem by affecting individual leaf size but not the number of leaves produced (Coaldrake, 1985) or initiated (Coaldrake and Pearson, 1985). Although reduced N nutrition in case of late sowing could indeed explain poorer biomass and yields, we expect that in our experiment, the application of the 60 kg N ha^{-1} to each sowing date treatment may be considered enough to mask the effect of the N flush. Past field trials have shown that maximum yields are generally obtained in the range of 30 to 60 kg N ha^{-1} (Akponikpè *et al.*, 2008; Christianson *et al.*, 1990; Bationo *et al.*, 1990b; Gérard and Buerkert, 2001), so any additional N would not be expected to have an effect.

Temperature amplitude and its interaction with photoperiod may have been the cause of the detrimental effect of sowing date. According to Coaldrake (1985), daylength controlled the time to panicle initiation by determining the number of leaves which had to be initiated before PI. But Coaldrake and Pearson (1986) showed that high temperature prior to PI increased the number of leaves initiated on the main stem and the size of the apical dome at the start of PI. This agrees with our results and may also increase the NPP, which depends on the apical dome size and is a main determinant of grain yield. The positive effect of temperature prior to PI on the size of apical dome could also explain in part the observed differences in grain number across sowing dates, which were similar in S1 and S2 and decreased for S3 and S4 (Table 3). The average temperature after sowing was 33.7±1.7 and 32.8±2.9 for S1 and S2 compared to 29.2±1.6 and 29.5±1.4 for S3 and S4 (mean±SD) over a twenty day period after sowing during which PI probably occurred (Table 3.2, Figure 3.4a). Temperatures (daily maximum, minimum and average) were close for S1 and S2 but were 5 to 10 °C lower for S3 and S4 (also close)(Figure 3.12a,b,c). Moreover there is a difference between air and soil temperature, the meristem temperature before initiation being closer to the soil one (Ong, 1983a).

3.4.2 Model performance

Although the APSIM-millet model performed well in the Indian environment where it had been thoroughly parameterized and tested, it could not adequately reproduce the behavior of Sahelian millet genotypes unless a substantial cultivar-specific parameterization was carried out. With Indian cultivars, Van Oosterom *et al.* (2001a) found TLI and TLA to be independent of cultivar and sowing date (or environment). This approach was not satisfactory for the Sahelian genotypes. The reason why the TLI and TLA parameterization according to cultivar and sowing date substantially improved the model performance was that these are very sensitive parameters and therefore small errors on them lead to large errors in the estimation of TLN that is a core variable which determines LAI, light interception, assimilation processes and yield. Moreover most crop growth models, including APSIM, still lack physiological functionality to adequately match genotype x environment (G x E) interactions. These models emphasize the interaction between temperature and photoperiod, but infer no physiological-genetic basis for the interaction (Ong and Everard, 1979; Yan and Wallace, 1998). Yan and Wallace (1998) proposed a genotype x temperature x photoperiod interaction GPT-model of phenology. But APSIM is up to now implementing a temperature x photoperiod phenology response model.

The model could not handle the phenology of the photosensitive cultivar Maewa. Phenology during the vegetative stage (from emergence to panicle initiation) involves two phases: a juvenile phase, during which panicle initiation is not possible, regardless of daylength (Caddel and Weibel, 1972) and a photo-sensitive phase which ends at panicle initiation. For short day plants, models (CERES, APSIM) generally consider that the duration of the vegetative phase increases linearly with increasing daylength (juvenile phase). Such a linear function was shown to be inappropriate to simulate very photosensitive sorghum cultivars in Mali (Folliard *et al.*, 2004). These authors proposed hyperbolic and threshold hyperbolic functions, with the last one performing better, but no millet growth model does as yet take this into account (Craufurd *et al.*, 1999). Implementing such an approach would require changes in the source code of APSIM, which was beyond the scope of this work.

LAI was not well simulated for all combinations of cultivars and sowing dates. The quality of the function governing individual leaf area determination in the APSIM millet model is cultivar specific (Figure 3.2). The initial APSIM millet module parameterization with Indian cultivars Van Oosterom *et al.* (2001b) also found such a cultivar-specific quality of this relation. In this study the relation between the area of the largest leaf (y0) and the total leaf number (TLN) for an axis was significant for Ankoutes, Hainikirey, ICMV and Maewa. But poor relation was observed between y0 and TLN for CIVT, Zatib and Zongo, but such a relation was forced for the APSIM model parameterization. More consistent individual leaf area determination function should be tested and implemented in the APSIM millet module to improve LAI simulation. Moreover in the Sahel, the recommended density of 10.000 hill ha^{-1} thinned to 3 plants $hill^{-1}$ leads to clumped and sparse canopy (Payne, 2000). In APSIM biomass accumulation is a function of intercepted radiation and radiation use efficiency RUE. Intercepted radiation is dependent on LAI, essentially assuming an even distribution of it, which is not the case in our system. These could be a potential source of error in LAI simulations.

Biomass yields were underestimated for S1 but grain yields were better simulated for all sowing dates and cultivars. Biomass yield and temporal LAI are dependent on the total number of tillers and leaf production. The tiller number provided in the model corresponds to productive tillers only (NPP) which explains why grain yield is better estimated than total biomass and LAI. The latter tends to be underestimated because of the existence of non-productive tillers and also senesced tillers which may contribute to LAI development but are not taken into account.

3.5 Conclusions

This study shows that late sowing had a cultivar-specific detrimental effect on most agronomic variables (TLN, LAI, stover and grain yield and components). Photoperiod effect was observed only for one cultivar (the landrace Maewa) which matured at the end of the rainy season independently of sowing date. Temperature played a major role in the effect of sowing date on millet development and yield as both a consequence of amplitude (and independently of photoperiod) and accumulation. Our findings demonstrate the benefit of early sowing giving better growth and yield for most cultivars and support Sahelian farmers' behavior not only for landraces but also for improved cultivars.

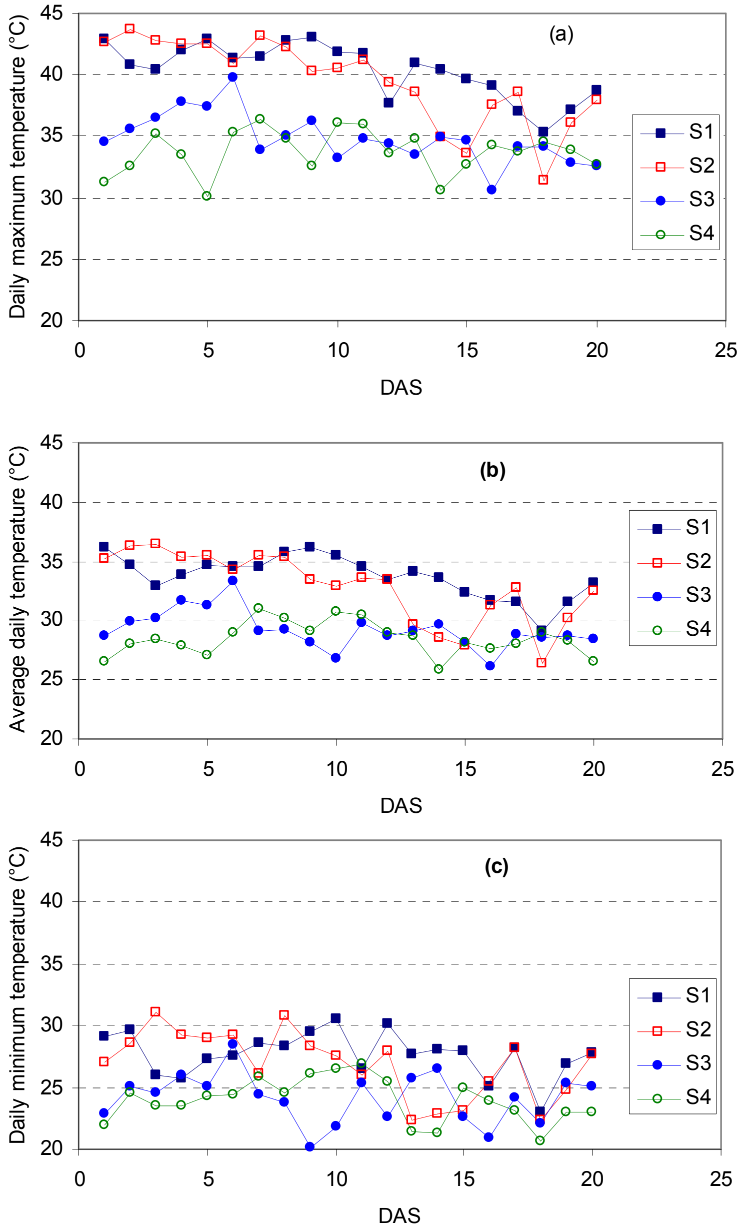

Figure 3.12. Maximum (a), average (b) and minimum (c) temperatures during a 20-day period after sowing (DAS) for the four sowing dates (S1 to S4).

The APSIM model could adequately reproduce the Sahelian millet genotype behavior in terms of phenology, development and yield when appropriate and substantial re-parameterization was done. Taking account of the difference in leaf dynamics (TLI and TLA) between sowing dates (due to temperature amplitude) and cultivar was decisive in the successful modeling exercise. To improve the APSIM-millet model, leaf dynamics should take account of genotype x temperature x photoperiod interaction and should not be constant across genotypes and environments. Our study succeeds in providing the, as yet unavailable, genetic and eco-physiological parameters for seven Sahelian millet cultivars. These parameters, though tested here only within the APSIM model, may also be used within any other dynamic crop simulation model and open the door for further modeling works in the area.

Chapter 4

Integrated nutrient management of pearl millet in the Sahel combining application of cattle manure, crop residue and mineral fertilizer.*

Abstract

In the Sahelian zone of Niger, integrated nutrient management relies on manure, millet stover and inorganic fertilizers as the main sources of nutrients to maintain or increase soil fertility, but each type of amendment presents its own limitations in terms of effectiveness, availability or side effects. There is therefore a need to develop guidelines regarding appropriate combinations of these 3 types of amendments. A fully factorial on-station experiment was conducted during the 1994 and 1995 rainy seasons at Sadoré, Niger. There were 3 factors with 3 levels each: (1) broadcast residue application (300, 900 and 2700 kg ha^{-1}) (2) broadcast cattle manure application (300, 900 and 2700 kg ha^{-1}), and (3) 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}). Manure and fertilizer increased millet yield in both years whereas residue was effective in 1995 only. The effects of manure and residue were additive compared to fertilizer with 300 kg ha^{-1} residue. The same conclusion applies to manure and fertilizer but only up to 50 kg N ha^{-1}. Synergetic effect was observed between residue and fertilizer in 1995 for stover and grain yield and was reflected in the partial factor productivity of N and P in both years. Two treatments stand out as particularly relevant in practice based on yield, water use efficiency, partial factor productivity and nutrient balance criteria: (1) a low input combination of 300 kg residue and 2700 kg manure ha^{-1} without fertilizer which leads to a 95% yield increase compared to the control (unfertilized +300 kg manure ha^{-1} +300 kg residue ha^{-1}); (2) a combination of 900 kg residue ha^{-1}, 2700 kg manure ha^{-1} and 15 kg N + 4 kg P ha^{-1} resulting in an average increase in grain yield of 132% compared to the control. There is a need for similar, long term experiments to confirm the present results.

Keywords: Pearl millet, manure, residue, fertilizer, water use efficiency, Sahel,

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4.1 Introduction

Pearl millet [*Pennisetum glaucum (L.) R.Br.*] is the major staple crop grown in the Sahelian region of Niger. In order to meet the nutritional requirements of the rapidly expanding population, millet production must be increased. This must be achieved by raising productivity rather than an expansion of cropland which is reaching a limit in many areas. Current productivity of millet-based cropping systems is very low, average millet grain yields seldom exceeds 500 kg ha^{-1} (De Rouw, 2004). Limited rainfall (300-600 mm) associated with frequent drought spells and high inter-annual rainfall variability, as well as unfavorable native soil fertility are the main reasons for the low productivity.

The nutrient balances of conventional cropping systems are, on average, negative indicating nutrient mining. (Smaling *et al.*, 1993) estimated that the annual average nutrient loss for sub-Saharan Africa would be of the order of 26 kg N, 3 kg P, and 19 kg K ha^{-1} in 2000. Although some authors have reported large responses to K fertilizer in the absence of crop residue restitution (Rebafka *et al.*, 1994), nutrient management strategies have generally focused on satisfying plant N and P requirements, the two most limiting nutrients (Bationo *et al.*, 2003). Although other management strategies such as long term vegetated fallowing and biological N fixation may also contribute positively to the N and P balance, manure, crop residue (residue) and inorganic fertilizers constitute the main potential sources of nutrients in the Sahel to prevent nutrient depletion, preserve the long term productivity of soils, and maximize nutrient use efficiency.

It has long been recognized that an integrated approach to nutrient management must be developed rather than rely on a single source of nutrients (Kimani *et al.*, 2003). Indeed, although the effectiveness of manure, crop residue or fertilizers for improving soil fertility and crop yields has been demonstrated repeatedly through on-station and on-farm trials (e.g. Bationo and Mokwunye, 1991a,b; Brouwer and Powell, 1998), all these sources are limited for farmers' use by either availability (Palm *et al.*, 1997), competing uses (Bationo *et al.*, 1995; Lamers *et al.*, 1998) and price or financial risk (Shapiro and Sanders, 1998). Hence, considering multiple sources of nutrients is a necessity. In addition, given that, on average, insufficient cattle manure (0.7 Mg ha^{-1} yr^{-1}; Palm et al., 1997) is available to satisfy crop requirements and that crop residue application corresponds to nothing but a recycling of nutrients within cropland, one must in part rely on the use of inorganic fertilizers to close the nutrient balance gap.

Integrated nutrient management (INM) relies on the use of various organic and inorganic sources of nutrients in order to achieve productive and sustainable agricultural systems (Palm *et al.*, 1997). A specific objective of INM is to maximize nutrient use efficiency (Kimani *et al.*, 2003). In millet-based rainfed systems, this goes along with a strong increase in water use efficiency, as seasonal cumulative evapotranspiration is little affected by fertility management practices (Payne, 2000). Besides the socio-economic reasons mentioned above (cost, availability, etc.), there are other very good reasons for combining different sources of nutrients. For instance, the use of inorganic N and P fertilizers alone is not advisable as in the long run it may lead to a decrease in soil organic content (SOC), soil acidification, decreasing base saturation, and a large increase in exchangeable Al (Kretzschmar *et al.*, 1991; Wendt *et al.*, 1993; Bationo *et al.*, 1995) or even reduce P availability to crops despite the addition of P fertilizer (Michels and Bielders, 2006). The sole application of fertilizer P, the most limiting nutrient for millet growth in the region (Geiger *et al.*, 1992) exacerbates the negative N and K balances (Buerkert *et al.*, 2000). Whereas fertilizers release their nutrients rather rapidly, manure or residue act as slow release fertilizers. In addition, they are a source of multiple nutrients, including micronutrients, supply carbon for soil micro-organisms involved in nutrient cycling, and may improve soil physical and chemical quality (Esse *et al.*, 2001; Buerkert *et al.*, 2000; Harris, 2002).

The use of either crop residue or manure can buffer soil acidification resulting from fertilizer use, thereby enhancing fertilizer use efficiency by preventing P immobilization (e.g. Hafner *et al.*, 1993b). Manure often has a residual effect which may last for two or more further growing seasons depending on the amount of manure applied (Esse *et al.*, 2001; Schlecht *et al.*, 2004; De Rouw and Rajot, 2004a). Previous works showed that short-term (1-2 years) and particularly long-term (5 years) application of residue significantly increased millet dry matter or grain yields whereas their omission resulted in an immediate yield decrease (Rebafka *et al.*, 1994; Buerkert and Lamers, 1999; Bielders *et al.*, 2002). Although no adverse effect was reported on millet production in the Sahelian zone of Niger for residue application rates up to 4 t ha^{-1} (Bationo *et al.*, 1993), the addition of millet stover may lead to a temporary immobilization of N as a result of its high C/N ratio. This may also apply to low quality manure, which is often the case of manure transported from village enclosures to the fields. This temporary immobilization may reduce the risk of N leaching or volatilization and thereby improve the overall nutrient use efficiency for combined application of residue or low quality manure with sources of readily available N such as mineral N fertilizer.

Additive, but also synergetic (more than proportional) effects have been reported in the literature as a result of the combined use of organic and inorganic amendments (Bationo *et al.*, 1993; Hafner *et al.*, 1993b; Buerkert *et al.*, 2000; Kimetu *et al.*, 2004). In Niger, phosphorus use efficiency for millet (kg grain / kg applied P) was increased from 46 on plots fertilized with inorganic P to 86 on plots amended with inorganic N and P and millet crop residue (Bationo *et al.*, 2003). In normal rainfall years, the application of millet residue doubled the P use efficiency of millet despite the very small contribution of residue to the total P supply (Bationo and Buerkert, 2001). On average over a 9-year experiment, Yamoah *et al.* (2002) reported that millet grain yield increased from 320 kg ha^{-1} on control plots to 700, 900 and 1510 kg ha^{-1} on plots amended with residue, N P fertilizer and residue+N P fertilizer, respectively. Similar trends were reported for millet stover yield. Water use efficiency was raised from 0.78 kg grain ha^{-1} mm^{-1} for the control to 3.61 kg ha^{-1} mm^{-1} for the residue+fertilizer plots. Fertilizer use efficiency (kg grain kg^{-1} fertilizer) was 13.5 for the fertilized plots and increased to 27.6 upon the addition of residue. Yamoah *et al.* (2002) concluded that the residue+fertilizer treatment had the highest sustainability yield index. These synergetic effects may result from the side effects of using organic fertilizers, besides their role as nutrient providers: P mobility enhancement, decrease in exchangeable Al, enhancement of root growth, decreased surface temperature and soil penetration resistance, and soil protection against wind erosion (Buerkert *et al.*, 2000; Bielders *et al.*, 2000).

Although several studies have evaluated the benefits of combining two sources of nutrients, none have evaluated the possible interactions resulting from the combined application of manure, crop residue and fertilizer. The objective of this paper was therefore to evaluate the effect of the combined application of those three types of amendments on millet production, water use efficiency, partial factor productivity and nutrient balances in a millet crop in order to derive practical recommendations for INM.

4.2 Materials and methods

4.2.1 Experimental site

The experiment was conducted at Sadoré, Niger (13°15'N, 2°17'E and 240 m of altitude) on the experimental station of the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), located 45 km south-west of Niamey, the capital city of Niger. The climate is typical of the Sahelian zone, with summer rainfall and high temperature throughout the year. The annual rainfall in Niamey is 545 mm and the average temperature is 29°C. The soil is classified as sandy, siliceous, isohyperthermic psammentic Paleustalf with 91% sand, 5% silt and 4% clay in the A horizon and a bulk density of about 1.65 Mg m^{-3} (West *et al.*, 1984). Soil water content at field capacity is 0.09 to 0.10 m^3 m^{-3} (Klaij and Vachaud, 1992).

4.2.2 Experimental design and crop management

The experiment was run in the 1994 and 1995 rainy seasons (with no irrigation) as a randomized complete block design with 3 replications. The experimental field had been cultivated in 1993 for a homogeneity trial without any inputs or tillage. Prior to this, it had been left fallow for more than 10 years and never used previously for experiments. Individual plot size was 10 x 20 m. There were 3 factors with 3 levels each: (1) broadcast millet stover application (stems with leaves) at a rate of 300, 900 and 2700 kg ha^{-1}, hereafter referred to as 300R, 900R and 2700R, respectively; (2) uniform cattle manure application at rates of 300, 900 and 2700 kg ha^{-1}, referred to as 300M, 900M and 2700M, respectively; and (3) mineral fertilizer application : no fertilizer, 15 kg N ha^{-1} + 4.4 kg P ha^{-1} and 45 kg N ha^{-1} + 13.1 kg P ha^{-1} referred to as 0N0P, 15N4P and 45N13P, respectively. In 1994, manure and residue application were delayed until 2 and 5 weeks after millet sowing, respectively, due to logistic constraints. The implications of this late application are discussed later. In 1995 residue was applied in January and manure approx. 4 weeks before sowing. N was applied as Calcium Ammonium Nitrate (CAN, 26% N) placed 0.1 m from pockets and incorporated with a hoe. In the case of 45N13P, the application of N was split in 2 (Table 4.1). P was broadcast prior to sowing as Single Super Phosphate (SSP, 18% P2O5) and incorporated with a light cattle-drawn implement. Additional management operations are reported in Table 4.1. Manure nutrient content was 1 0.05% N, 0.2

Table 4.1. Crop management in 1994 and 1995

	1994	1995
Sowing date	6 June	20 June
Residue application	14 July	15 January
Manure application	20-21 June	17-18 May
Fertilizer application	N: 7 July (15 kg N ha^{-1}), 25 july (30 kg N ha^{-1}) P: 20 June	N: 12 July (15 kg N ha^{-1}), 11 August (30 kg N ha^{-1}) P: 11 May
Weeding (manually with hilaire)	21 June 25 July 9-10 August	3-7 July 7-11 August
Pest and bird management	Weekly Deltamethrine spray (after 11 august) and Bird guard	Weekly Deltamethrine spray (after 14 August) and Bird guard
Final harvest	20-23 September	26-27 September

Table 4.2. Amounts of nitrogen, phosphorus, and potassium in manure and millet residue applied to field plots at the onset of the experiment. Values in bracket denote standard deviations, (n = 5). Values for residue were computed using the weighted average nutrient content of stems and leaves in 1994 and 1995.

	Amount (kg ha^{-1})	Total N (kg ha^{-1})	Total P (kg ha^{-1})	Total K (kg ha^{-1})
Manure	300	3.01 (0.14)	0.6 (0.02)	4.81 (0.26)
	900	9.04 (0.43)	1.81 (0.05)	14.42 (0.79)
	2700	27.11 (1.28)	5.42 (0.15)	43.26 (2.36)
Residue	300	2.32 (-)	0.15 (-)	7.27 (-)
	900	6.97 (-)	0.44 (-)	21.8 (-)
	2700	22.9 (-)	1.32 (-)	65.46 (-)

0.01% P and 1.6 0.09% K (mean SD; n = 5). The manure and residue nutrient supply corresponding to the different application rates are given in table 2.

The millet cultivar CIVT (Composite Inter-varietal de Tarna, early maturing, 95 days) was sown in pockets on untilled soil after the first rainfall event exceeding 20 mm, at a density of 12500 pockets ha^{-1} and 2 plants pocket^{-1} in 1994, and at a density of 10000 pockets ha^{-1} and 3 plants pocket^{-1} in 1995.

4.2.3 Data collection and analysis

Daily rainfall data was recorded by means of an automatic rainfall gauge located at the experimental station. Soil moisture measurements were made in all the plots with an on-site calibrated neutron probe (Didcot) at approximately 10-day intervals throughout the growing season from 0.15 to 2.1 m depth at 0.15 m intervals. A separate calibration was used for 0.15 m and all depths > 0.15 m. Details of the method used to compute the water balance (change in soil water stock, drainage at maximum rooting depth (1.5 m) and evapotranspiration) from water content data were given by Klaij and Vachaud (1992). The following function, derived from the field moisture profiles, was used to relate average volumetric moisture content at drainage depth (θ; [m^3

m^{-3}]) and drainage flux (J; [mm day^{-1}] :

$$J = 4.829 \cdot 10^{-5} \cdot \theta^{4.196} \tag{4.1}$$

Water use efficiency (WUE) was computed as the ratio of grain yield to total evapotranspiration during the course of the cropping cycle. Readily available soil water for plants (PAW; mm) was estimated between the soil surface and the rooting depth using the following equation :

$$PAW_j = \sum_{i=1}^{n_j} (\theta_{i,j} - \theta c_{i,j}) \cdot \Delta z_i \tag{4.2}$$

for all i such that $\theta_i \geq \theta c_i$, where the subscripts i and j represent soil layers and time, respectively; θ_i is the average measured VWC [m^3 m^{-3}] of layer i; θc_i is the critical volumetric water content (CWC) of layer i; and Δz_i [mm] represents the thickness of each layer. CWC is defined as the volumetric water content below which millet starts to experience water stress as described in Bielders and Michels (2002). Rooting depth was calculated on the basis of a constant root growth rate of 0.02 m per day, irrespective of the treatment, up to a maximum rooting depth of 1.5 m (Bielders and Michels, 2002).

Soil samples were taken in 1994 prior to sowing in each plot at depths of 0.0-0.2 and 0.2-0.4 m. Each sample was analysed for pH(H2O) (NH4AcO at pH 7; soil/water ratio of 1:2.5), organic carbon (Walkley and Black), total N (Kjeldhal), available phosphorus (Bray1) and exchangeable aluminum (KCl extraction). Samples of millet leaves, stems and grain were analyzed for total N, P, and K content in each plot in 1994 and 1995 at harvest. Partial factor productivity refers to the ratio of grain yield to the total nutrient application rate (Pandey *et al.*, 2001a). A simplified nutrient balance was calculated by subtracting the amount of N, P, or K exported with the harvest (grain, stems and leaves) from the total amount of N, P, or K added through manure, residue and fertilizer. All results were submitted to analysis of variance in GenStat 6 (Laws Agricultual Trust, 2002) using a randomized complete block structure with 3 treatments and 3 replications in which the 2 years were considered as split-plot levels. When year by treatment interaction was significant, the analysis was done for each year. A log transformation was applied to the partial productivity data of all 3 nutrients because of non normality. Differences between treatments were considered at error probabilities $\leq$ 0.05, 0.01 or 0.001.

4.3 Results

4.3.1 Rainfall characteristics

The rainfall during the cropping period was 721 mm in 1994 and 431 mm in 1995, whereas for the whole year it was 794 mm in 1994 and 486 mm in 1995 (Figure 4.1). The latter corresponds respectively to 146 and 89% of the long term annual average. Rainfall was more evenly distributed in 1995 than in 1994 despite the higher rainfall amount during the 1994 cropping cycle.

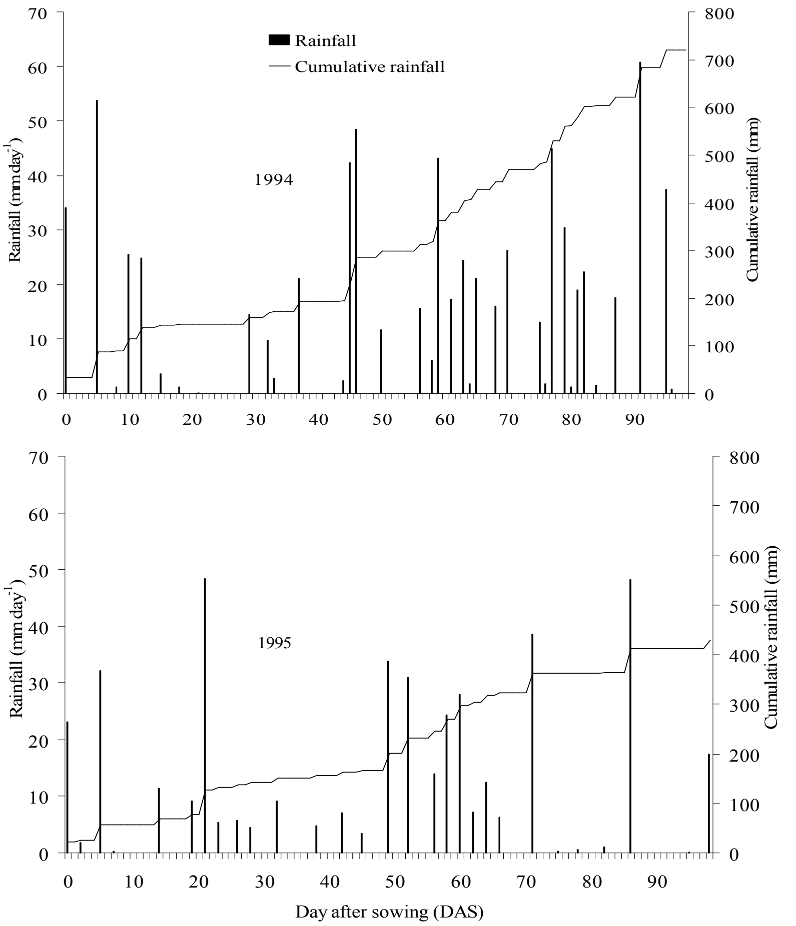

Figure 4.1. Daily and cumulative rainfall in 1994 and 1995 at ICRISAT Sahelian center, Sadoré, Niger

In 1994 there were 37 rainfall events during the cropping cycle, 6 of which exceeded 40 mm whereas in 1995 two events out of 29 exceeded this threshold. A dry spell of 16 days occurred from 13 to 28 days after sowing (DAS; juvenile stage) in 1994. In 1995 two dry spells were observed, from 22 till 50 DAS and from 72 to 85 DAS (maturing stage). However, since PAW did not reach critically low levels during those dry spells (Figure 4.2), no severe drought stress is expected in either year.

4.3.2 Initial soil chemical properties prior to the experiment

Differences were highly significant ($p < 0.001$) between depths for all parameters (Table 4.3). The $pH_{(H2O)}$ was acidic for all plots and depths. The soil was very poor in organic carbon, total N, and available P, decreasing with depth. Exchangeable Al content was fairly high and increased with depth as a result of the decreasing pH. All

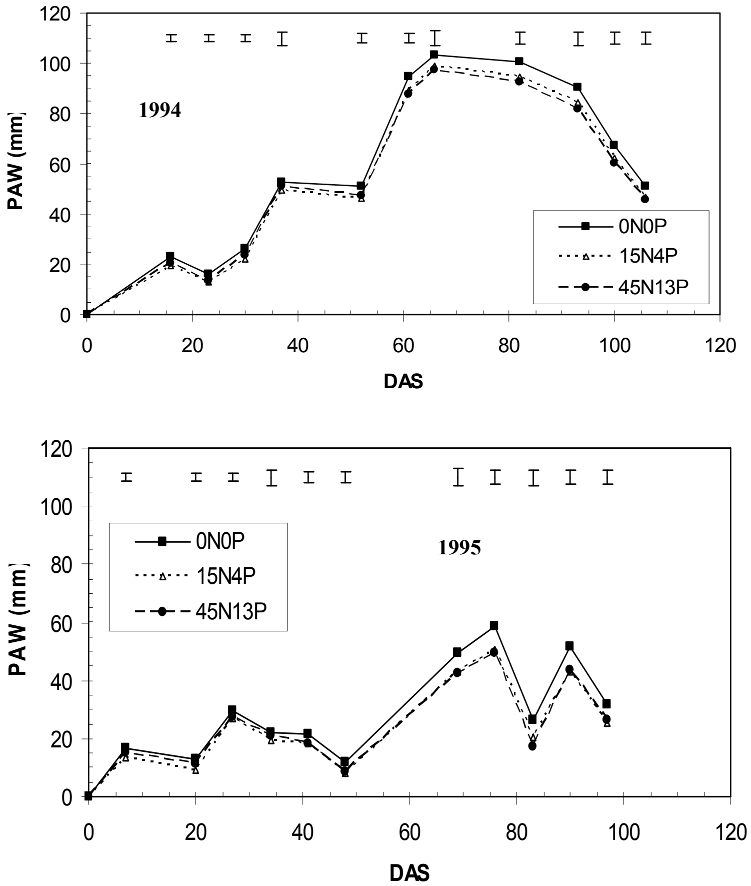

Figure 4.2. Change in plant available water (PAW) during the growing seasons of 1994 and 1995 as affected by fertilizer application. Error bars indicate the standard error of the difference (P = 0.05).

Table 4.3. Initial soil chemical characteristics of plots at two depths before the onset of the experiment in 1994 at ICRISAT Sahelian center, Sadoré, Niger. Values in bracket denote standard deviations (n = 87).

Depth (m)	Total N ($mg\ kg^{-1}$)	Available P ($mg\ kg^{-1}$)	Organic carbon (%)	$pH_{(H2O)}$ (-)	Exchangeable Al ($cmol\ kg^{-1}$)
0. 00 - 0.20	163 (30)	2.1 (0.5)	0.18 (0.04)	5.4 (0.1)	0.11 (0.06)
0. 20 - 0.40	132 (22)	1.5 (0.4)	0.14 (0.03)	5.3 (0.1)	0.25 (0.1)

properties are typical of the sandy soils of the region. The low P-Bray values clearly indicate the absence of prior P fertilization.

4.3.3 Millet stover

Overall millet stover yield was significantly higher in 1994 (1658 kg ha^{-1}) than in 1995 (1337 kg ha^{-1}) ($p < 0.001$). A year by treatment interaction was observed only in the case of residue application (p = 0.001). The addition of residue had no effect in 1994 but significantly increased millet stover yield in 1995 (p = 0.002, Table 4.4) when millet stover yield was increased by 14% and 23% for 900R (1360 kg ha^{-1}) and 2700R (1461 kg ha^{-1}), respectively, compared to 300R (1189 kg ha^{-1}; s.e.d. = 73 kg ha^{-1}). Significant effects of both fertilizer ($p < 0.001$) and manure ($p < 0.05$) application in 1994 and 1995 were observed (Table 4.4). On average over the 2 years, fertilizer improved stover yield by 40% and 67% for 15N4P (1537 kg ha^{-1}) and 45N13P (1841 kg ha^{-1}), respectively, compared to the no-fertilizer treatments 0N0P (1099 kg ha^{-1}; s.e.d. = 109 kg ha^{-1}). On average over the 2 years, manure application increased stover yield by 23% and 27% for 900M (1575 kg ha^{-1}) and 2700M (1625 kg ha^{-1}), respectively, compared to the 300M (1277 kg ha^{-1}; s.e.d. = 109 kg ha^{-1}).

There was no interaction between any of the treatments regarding stover yield in 1994 (Table 4.4). However, significant Res x Fert (p = 0.003) and Fert x Man interactions (p = 0.006) were observed in 1995 (Table 4.4). Whereas the addition of 45N13P more than doubled stover yields compared to the 0N0P in the presence of 900R and 2700R, for 300R the increase in stover yield was only 48% after adding 45N13P (Figure 4.3a). With respect to the Fert x Man interaction, one observes that the response to fertilization is similar in the presence of 300M and 900M, but there was no response to the highest rate of fertilization (45N13P) in the presence of 2700M compared to the 15N4P treatment (Figure 4.3b).

4.3.4 Millet grain yield

Contrary to stover yield, average millet grain yield was better in 1995 (785 kg ha^{-1}) than in 1994 (642 kg ha^{-1}). There was a strong year effect ($p < 0.001$), and a year by treatment interaction was observed in the case of residue application ($p < 0.001$). The addition of residue significantly increased millet grain yield in 1995 (p = 0.001) but had no effect in 1994 (Table 4.4; Figure 4.4a). In 1995, grain yield was improved

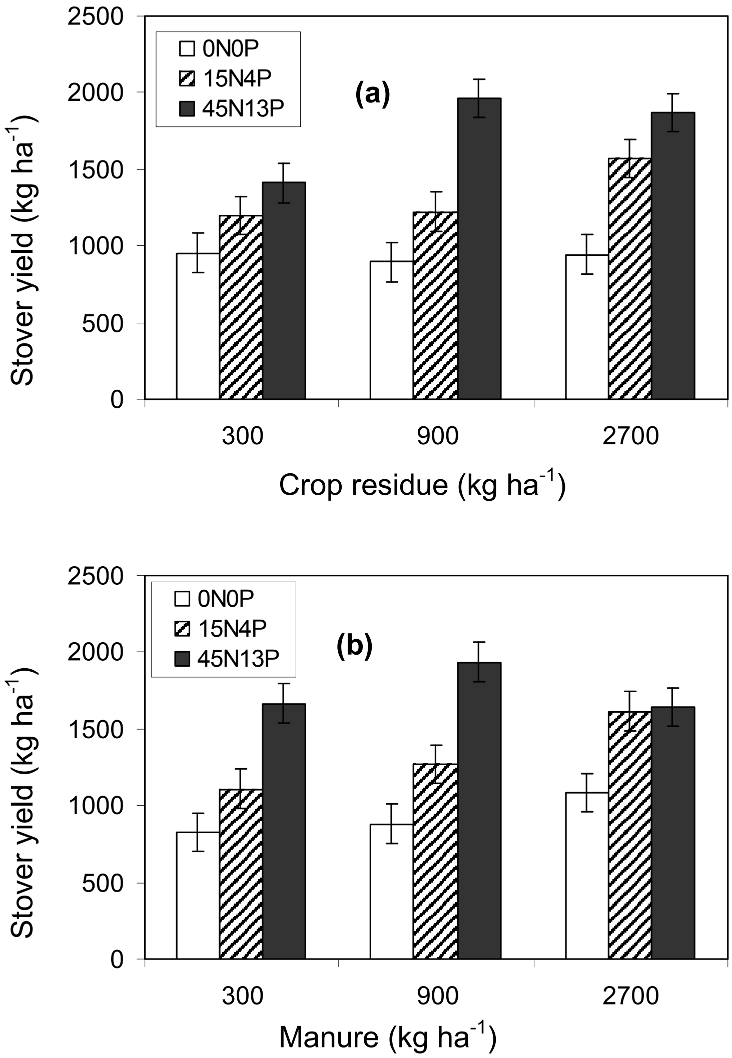

Figure 4.3. Millet stover yield as affected by combined application of cattle manure, millet residue and mineral fertilizer (N, P) in 1994 and 1995 at ICRISAT Sahelian center, Sadoré, Niger. Error bars denote s.e.d. Values are interaction means; (a) residue x fertilizer, (b) manure x fertilizer.

Table 4.4. Analysis of variance of millet stover and grain yield as affected by combined application of cattle manure (Man), millet residue (Res) and mineral fertilizer (Fert) in 1994 and 1995 at ICRISAT Sahelian center, Sadoré, Niger

		Stover				Grain			
		1994		1995		1994		1995	
	df	v.r.	F pr.	v.r.	F pr.	v.r.	F pr.	v.r.	F pr.
Res	2	1.28	n.s.	7.12	**	0.97	n.s.	8.92	***
Fert	2	8.90	***	62.83	***	13.09	***	63.87	***
Man	2	4.16	*	5.93	**	4.38	**	7.06	**
Res x Fert	4	0.9	n.s.	4.66	**	1.36	n.s.	3.86	**
Res x Man	4	0.52	n.s.	0.30	n.s.	0.90	n.s.	0.19	n.s.
Fert x Man	4	1.51	n.s.	4.06	**	0.76	n.s.	2.32	n.s.
Res x Fert x Man	8	0.75	n.s.	1.49	n.s.	1.20	n.s.	0.44	n.s.
Residuals	52								
CV(%)			36.5		20.2		37.8		22.1

df = degree of freedom; v.r.= variance ratio; n.s. = not significant;

*, **, *** probability significant at 0.05, 0.01, 0.001 respectively.

by 18% and 29%, respectively for 900R and 2700R compared to 300R.

In both years, increased application rates of fertilizer ($p < 0.001$) and manure ($p < 0.05$) significantly increased grain yields (Table 4.4). On average over the two years, manure increased grain yield by 19% and 29% for 900M (733 kg ha^{-1}) and 2700M (789 kg ha^{-1}), respectively, compared to the 300M (613 kg ha^{-1}; s.e.d. = 47 kg ha^{-1}). Overall, fertilizer improved grain yield by 40% and 86% for 15N4P (699 kg ha^{-1}) and 45N13P (933 kg ha^{-1}), respectively, compared to the no fertilizer (503 kg ha^{-1}; s.e.d. = 47 kg ha^{-1}) treatments. However, fertilizer response was significantly higher in 1995 than in 1994 (p = 0.009; Figure 4.4b).

A significant Res x Fert interaction for millet grain yield was observed in 1995 (p = 0.008), similar to that of millet stover yield. Whereas the addition of 45N13P increased grain yields by 129% and 113% in the presence of 900R and 2700R, respectively, compared to the 0N0P, for 300R the increase was only 49% following the application of 45N13P (Figure 4.4c).

4.3.5 Water balance, PAW and water use efficiency

There was no significant difference between seasonal cumulative millet evapotranspiration and drainage with regard to any of the treatments in 1994 and 1995. Average seasonal millet evapotranspiration was 459 mm in 1994 and 286 mm in 1995. Drainage was estimated at 158 and 44 mm in 1994 and 1995, respectively. There was no significant correlation between ET and either grain or stover yield in 1994 and 1995.

There is a significant fertilizer effect on all dates in 1994 except 37 and 66 DAS, and on 20, 40, 47, 83 and 90 DAS in 1995 (Figure 4.2). In both years, increased fertilizer application resulted in lower PAW, especially toward the end of the growing season. This is likely the result of additional water uptake following greater aboveground biomass (leaf area) development in fertilized treatments. However, the absolute dif-

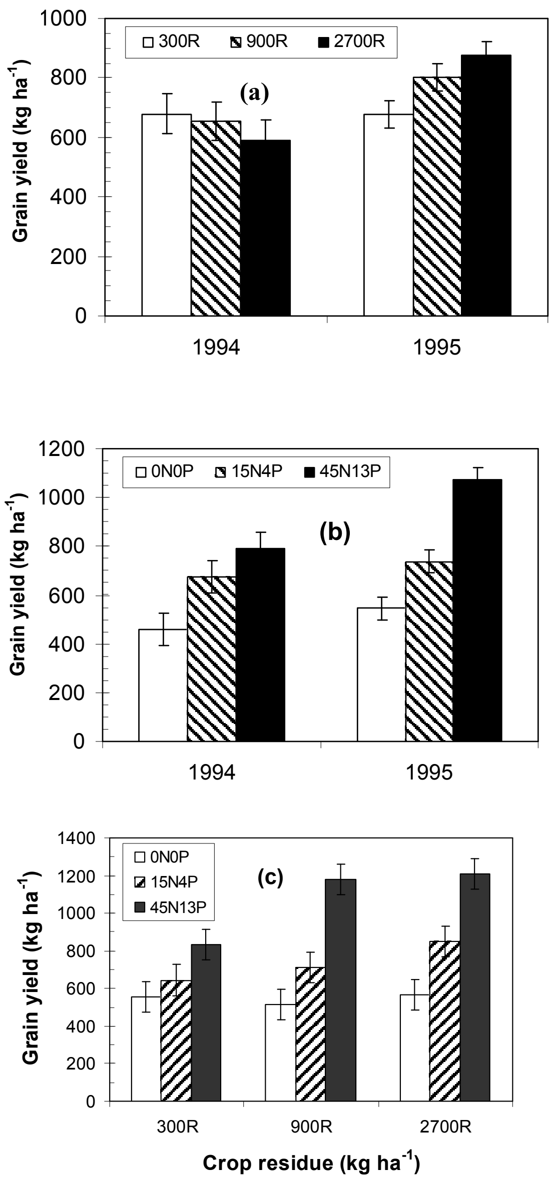

Figure 4.4. Millet grain yield as affected by combined application of cattle manure (M), residue (R) and mineral fertilizer (N, P) in 1994 and 1995 at ICRISAT Sahelian center, Sadoré, Niger. Error bars denote s.e.d. Values are interaction means; (a) year x residue, (b) year x fertilizer, (c) residue x fertilizer

ference in PAW between 0N0P and 45N13P remained small and reached at most 9 mm. In 1995, there was a significant Fert x Man interaction regarding PAW between 83 and 97 DAS.

PAW decreased as fertilization rate increased for 300M and 900M, but for 2700M, the effect of fertilization on PAW was negligible (not shown). This may largely result from the fact, in the presence of 2700M, stover yield at high rates of fertilizer (45N13P) were not different from yields achieved with 15N4P (Figure 4.3). Water use efficiency (WUE) on a grain basis was significantly different among both years ($p < 0.001$). In 1995, WUE was on average twice as high (2.76 kg ha^{-1} mm^{-1}) as in 1994 (1.40 kg ha^{-1} mm^{-1}) as a result of the higher grain yields and lower seasonal ET in 1995. In 1994, WUE showed significant differences for fertilizer ($p < 0.001$) and manure application ($p < 0.05$) (Table 4.5). Overall the WUE was increased by 40% and 76% for the 15N4P and 45N13P, respectively, compared to the control (0N0P; 1.00 kg ha^{-1} mm^{-1}). Increasing manure application from 300 to 900 kg ha^{-1} resulted in a 29% increase in WUE from 1.16 to 1.50 kg ha^{-1} mm^{-1}. The application of 2700 kg ha^{-1} manure only resulted in a small additional increase in WUE compared to the 900M (1.54 kg ha^{-1} mm^{-1}; s.e.d. = 0.14 kg ha^{-1} mm^{-1}).

Residue ($p < 0.001$), fertilizer ($p < 0.001$) and manure ($p < 0.01$) application all had a significant effect on WUE in 1995 (Table 4.6). WUE was 2.34, 2.80 and 3.14 kg ha^{-1} mm^{-1} for the 300R, 900R and 2700R treatments respectively (s.e.d. = 0.18 kg ha^{-1} mm^{-1}). Overall the WUE was increased by 29% and 98% for the 15N4P and 45N13P, respectively, compared to the control (0N0P; 1.94 kg ha^{-1} mm^{-1}). However, there was a significant Res x Fert interaction ($p = 0.05$): the improvement in WUE following fertilizer addition was much stronger at 900R and 2700R than at 300R (Figure 4.5).

There is a high positive correlation between WUE and grain yield (Figure 4.6). On average, a yield increase of 100 kg grain ha^{-1} resulted in a gain of 0.21 and 0.34 kg ha^{-1} mm^{-1} in WUE in 1994 and 1995, respectively.

4.3.6 Partial factor productivity (PFP) of N, P and K

As a result of the higher grain yields in 1995 compared to 1994, partial factor productivity (on a grain basis) of N (23.6 kg grain kg^{-1} N), P (141.7 kg grain kg^{-1} P), and K (21.1 kg grain kg^{-1} N) in 1995 was higher than in 1994 (20.3 kg grain kg^{-1} N, 121.4 kg grain kg^{-1} P, 18.4 kg grain kg^{-1} K).

In 1994, all three types of amendments had a significant effect on the PFP of N, P and K on a grain yield basis (Table 4.5). For N and P, PFP decreased with increasing application rates of residue, manure or fertilizer (not shown). This is an immediate consequence of the fact that substantial yields are being achieved for the 300R, 300M or 0N0P treatments and that yield increases in response to residue, manure and fertilizer are fairly modest. For K, the PFP also decreased with increasing rates of manure and residue, for similar reasons. Following fertilizer additions, however, the PFP of K increased with increasing fertilization because adding fertilizer increased yields yet neither CAN nor SSP provide any K.

There was a significant Res x Fert interaction in 1994 (Table 4.5) for N (Figure

Table 4.5. Analysis of variance of water use efficiency (WUE), as well as partial factor productivity of N (PNP), phosphorus (PPP) and potassium (PKP) as affected by combined application of cattle manure (Man), millet residue (Res) and mineral fertilizer (Fert) in 1994 at ICRISAT Sahelian center, Sadoré, Niger

		WUE		PNP		PPP		PKP	
	df	v.r.	F. pr.	v.r.	F. pr.	v.r.	F. pr.	v.r.	F. pr.
Res	2	0.88	n.s.	22.49	***	8.05	***	73.18	***
Fert	2	14.88	***	12.59	***	45.75	***	13.68	***
Man	2	4.35	*	10.62	***	14.27	***	17.56	***
Res x Fert	4	1.22	n.s.	7.09	***	5.51	***	2.65	*
Res x Man	4	1.26	n.s.	0.61	n.s.	0.82	n.s.	1.26	n.s.
Fert x Man	4	0.91	n.s.	3.73	*	7.65	***	0.98	n.s.
Res x Fert x Man	8	0.85	n.s.	0.85	n.s.	0.98	n.s.	1.27	n.s.
Residuals	52								
CV(%)			37.0		16.8		10.5		18.1

df = degree of freedom; v.r.= variance ratio; n.s. = not significant;

*, **, *** probability significant at 0.05, 0.01, 0.001 respectively.

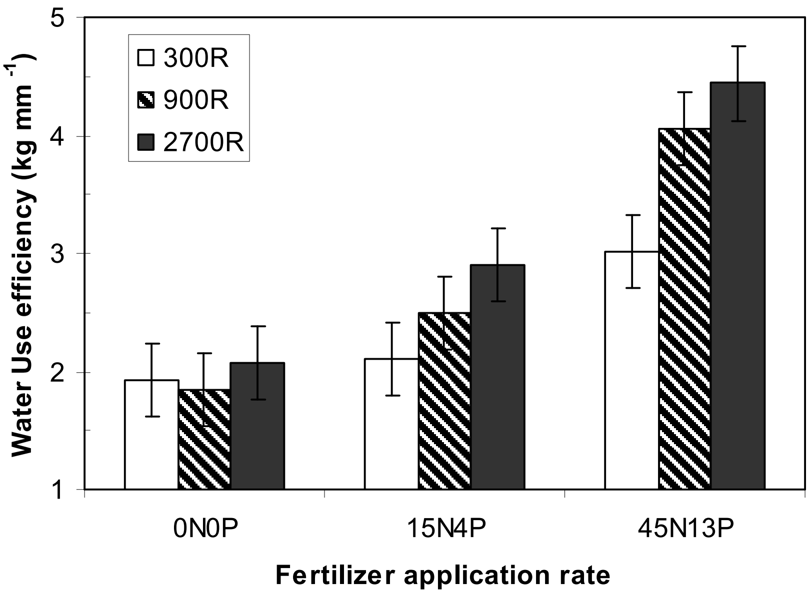

Figure 4.5. Effect of crop residue (R) and fertilizer application (N, P) on millet water use efficiency in 1995 at ICRISAT Sahelian center, Sadoré, Niger. Error bars denote s.e.d. Values are interaction means

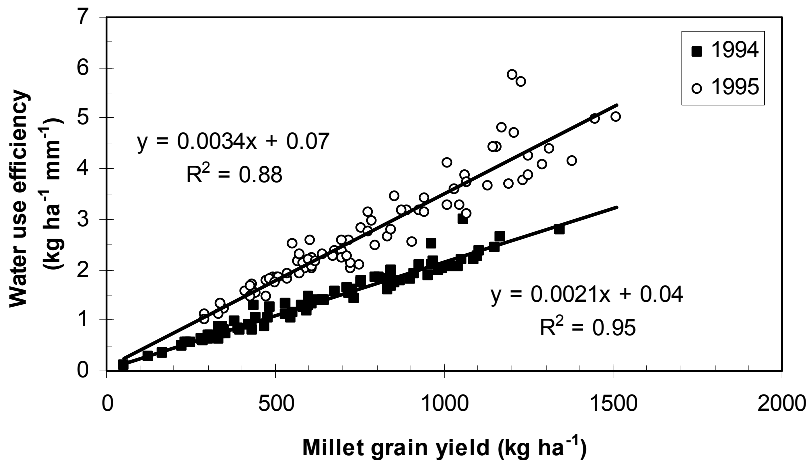

Figure 4.6. Water use efficiency as a function of millet grain yield in 1994 and 1995 at ICRISAT Sahelian center, Sadoré, Niger.

4.7a) and P (not shown). The PFP of N (or P) decreased rapidly with increasing rate of fertilizer application at low levels of residue (300R), yet at higher rates of crop residue, the PFP of N (or P) decreased much less or even remained rather stable for the various fertilizer application rates. This is an immediate consequence of the poor yield response to fertilizer at low levels of crop residue. At higher levels of crop residue, millet is better able to take up the nutrients added through fertilizer, which leads to a fairly constant partial N productivity of about 10 kg grain kg^{-1} N at the highest rate of fertilization in the presence of 2700R. There was also a significant Res x Fert interaction in 1994 for the partial K productivity (Table 4.5; Figure 4.7b). The increase in the partial K productivity following fertilization was significant only for the two highest residue application rates in the presence of 2700R.

A significant Fert x Man interaction was observed for the PFP of N and P in 1994 (Table 4.5). At the highest rate of fertilization, there was little effect of manure application on the partial N productivity, whereas for 0N0P and 15N4P the partial N productivity decreased with increasing manure application, and this decrease in PFP was strongest at the lowest fertilizer rate (not shown). A similar response was observed for P (not shown). As in 1994, the application of residue, fertilizer and manure had a significant effect on the PFP of N and K in 1995 (Table 4.6). Although fertilizer and manure had a significant effect on the PFP of P, residue application did not (Table 4.6). There were significant Res x Fert (N, P), Res x Man (N, K) and Fert x Man (N, P) interactions as well as a Res x Fert x Man (N) interaction (not shown). The Res x Fert and Fert x Man interactions for N and P were similar to 1994. At the highest rate of fertilization, there was little effect of residue (or manure) application on the partial factor productivity of N and P, whereas for 0N0P and 15N4P the partial factor productivity of N and P decreased with increasing residue (or manure) application, and this decrease in PFP was strongest at the lowest fertilizer rate (not shown). Regarding

Table 4.6. Analysis of variance of water use efficiency (WUE), as well as partial factor productivity of N (PNP), phosphorus (PPP) and potassium (PKP) as affected by combined application of cattle manure (Man), millet residue (Res) and mineral fertilizer (Fert) in 1995 at ICRISAT Sahelian center, Sadoré, Niger

		WUE		PNP		PPP		PKP	
	df	v.r.	F. pr.	v.r.	F. pr.	v.r.	F. pr.	v.r.	F. pr.
Res	2	9.93	***	16.72	***	0.84	n.s.	129.3	***
Fert	2	59.05	***	37.69	***	166.2	***	56.19	***
Man	2	5.43	**	28.60	***	44.45	***	53.36	***
Res x Fert	4	2.55	*	12.88	***	8.11	***	2.54	n.s.
Res x Man	4	0.41	n.s.	3.54	*	1.97	n.s.	11.99	***
Fert x Man	4	1.67	n.s.	4.84	**	15.70	***	2.33	n.s.
Res x Fert x Man	8	0.45	n.s.	2.27	*	2.06	n.s.	0.7	n.s.
Residuals	52								
CV(%)			23.7		7.9		5.1		8.5

df = degree of freedom; v.r.= variance ratio; n.s. = not significant;

*, **, *** probability significant at 0.05, 0.01, 0.001 respectively.

the Res x Man interaction for N and K, the decrease in PFP as residue application rate increased was strongest at the lowest manure application rate (300M). At high rates of manure (2700M), increasing residue had little effect on the PFP of N (Figure 4.8) and K (not shown).

4.3.7 Nutrient balances

Average nutrient balances were positive in 1994 (13.5 kg N, 5.3 kg P and 6.1 kg K ha^{-1}) and in 1995 (19.3 kg N, 6.2 kg P and 11 kg K ha^{-1}). However, large differences were observed between treatments, ranging from -17.7 to 53.7 kg ha^{-1} for N, -2 to 15.7 kg ha^{-1} for P and -39.7 to 87.3 kg ha^{-1} for K. In 1994, there were significant residue ($p < 0.001$), fertilizer ($p < 0.001$) and manure ($p < 0.001$) effects on the N, P and K balances, but no significant interactions (Table 4.7). In general, the nutrient balances increased as the application rate of amendments increased, except for the K balance which decreased as the application rate of fertilizer increased. In 1995, there were also significant residue ($p < 0.001$ for N and K, $p < 0.05$ for P), fertilizer ($p < 0.001$) and manure ($p < 0.001$) effects on the N, P and K balances, with similar trends as in 1994 (Table 4.7). In addition, there was a significant Res x Fert interaction for N ($p = 0.025$) and P ($p = 0.002$). As the rate of fertilizer application increased, the positive impact of increasing residue application rates on the N and P balances became less and less marked (not shown). Table 4.8 highlights which treatments presented neutral or positive balances for all 3 elements and in what year. At residue application rates of 2700 kg ha^{-1}, all combinations of manure and fertilizer were positive. At intermediate residue application rates (900R), all treatments involving 2700 kg manure ha^{-1} presented positive balances in both years. At 300R, positive balances were observed in both years only for the highest and lowest fertilization treatments in combination with 2700 kg ha^{-1} manure.

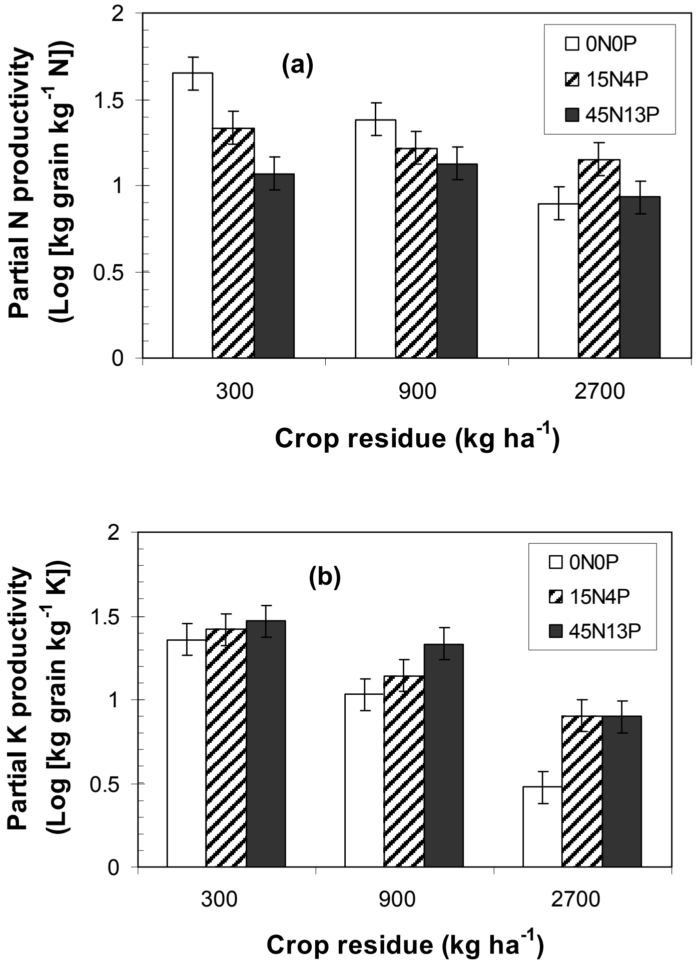

Figure 4.7. Effect of crop residue and fertilizer on the partial factor productivity of N (a) and K (b) in 1994. Error bars are s.e.d. Values are interaction means.

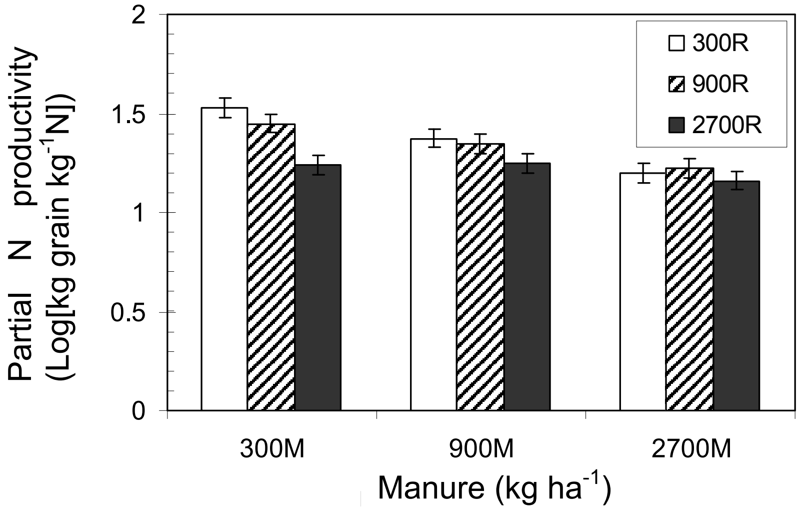

Figure 4.8. Effect of crop residue and manure on the partial factor productivity of N in 1995. Error bars are s.e.d. Values are interaction means.

Table 4.7. Average effect of the application of millet residue (kg ha^{-1}), fertilizer and manure (kg ha^{-1}) on nutrient (N, P, K) balances in 1994 and 1995.

		1994			1995		
		N	P	K	N	P	K
			——kg ha^{-1}——			——kg ha^{-1}——	
Residue	300	3.9	4.6	-18.7	14.5	6.2	-5.7
	900	10.0	5.1	-4.0	16.3	6.0	3.8
	2700	26.5	6.1	41.0	26.9	6.52	35
	F pr.	***	***	***	***	***	***
Fertilizer	0N0P	1.5	0.5	16.9	7.7	1.5	23.1
	15N4P	7.2	3.7	3.9	15.8	5.0	10.0
	45N13P	31.6	11.6	-2.5	34.2	12.2	0.1
	F pr.	***	***	***	*	***	***
Manure	300	8.4	3.7	-1.1	11.3	4.7	-0.8
	900	6.7	4.3	-4.7	15.4	5.4	5.4
	2700	25.3	7.81	24.1	31.1	8.6	28.6
	F pr.	***	***	***	***	***	***
	s.e.d.	2.93	0.4	4.6	1.6	0.21	2.9
	CV (%)	31.5	13.5	118	12.4	1.6	44.7

*, **, *** probability significant at 0.05, 0.01, 0.001 respectively.

Table 4.8. Classification of the 27 residue x fertilizer x manure treatment combinations according to their N, P, and K balances in 1994 and 1995. The number in each cell represents the year in which the balances were positive or neutral.
a

		Manure		
Residue	Fert	300	900	2700
300	0N0P	-	1995	1994-95
	15N4P	-	1995	1995
	45N13P	-	-	1994-95
900	0N0P	1995	1995	1994-95
	15N4P	1994	1995	1994-95
	45N13P	-	-	1994-95
2700	0N0P	1994-95	1994-95	1994-95
	15N4P	1994-95	1994-95	1994-95
	45N13P	1994-95	1994-95	1994-95

[a]neutral balance refers to balances within 20% of the average nutrient exported by the experiment : $-2.5 < N < 2.5$ kg ha^{-1}; $-0.3 < P < 0.3$ kg ha^{-1}; $-5 < K < 5$ kg ha^{-1}

4.4 Discussion

For this research to be relevant in the context of Sahelian INM, reasonable rates of organic inputs were used: 300 to 2700 kg ha^{-1} of residue or manure. Regarding manure, recommendation was made not to exceed 2500 kg manure ha^{-1} yr^{-1} (Brouwer and Powell, 1998; Gandah *et al.*, 2003a) to minimize leaching of nutrients. Average millet stover production in the Sahel is of the order of 1300 kg ha^{-1} but for high input systems stover yields in excess of 6000 kg ha^{-1} have been reported (Yamoah *et al.*, 2002). In the present experiment, stover yields reached at most 2700 kg ha^{-1}. However, average stover yield for all the treatment combinations involving 2700 kg residue ha^{-1} was 1490 kg ha^{-1}. Hence, these treatment combinations could not be sustained without external input of residue. On the contrary, treatments involving 300R and 900R produced 1178 and 625 kg stover ha^{-1}, respectively, in excess of their mulching requirement. Treatment combinations involving 300R and 900R can therefore easily be sustained.

Traditionally, the results of fertility management trials have been compared to zero-input control plots. Such plots invariably suffer from rapid acidification and severe nutrient deficiency (e.g. Buerkert and Lamers, 1999; Bielders *et al.*, 2002) which is not representative of traditional farmers fields. In the present study, 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 representative of the amount of residue present in farmer fields at the start of the rainy season. De Rouw and Rajot (2004a) estimated that passing herds leave behind about 100 kg ha^{-1} of dung. The manure application rates used here for the control are therefore only slightly larger than what would be expected to be deposited by grazing animals.

4.4.1 Millet response to INM

Grain yields were higher in 1995 than 1994 despite lower rainfall and generally lower values of PAW in 1995. Wang *et al.* (2007) combining N and P fertilizer, maize stover and cattle manure in a long term experiment, also found a year effect on maize grain yield in northern China that was ascribed to the effect of the amount of rain during the growing season and the soil water content at sowing. The year effect often observed in agricultural experiments in the Sahel is to a large extent induced by the rainfall pattern (Christianson *et al.*, 1990; Sivakumar and Salaam, 1999; Gandah *et al.*, 2003a). The high drainage observed in 1994 could be attributed to the high total seasonal rainfall and numerous heavy rainfall events (6 exceeding 40 mm registered during the cropping cycle), which may have resulted in important N leaching during that year and N deficiency towards the end of the growing season, even for highly fertilized treatments. In 1995, lower PAW during the early growing season may have constrained biomass production compared to 1994, yet appears to have had little impact on grain production.

Although 1994 was fairly wet and 1995 fairly dry, the two years of experimentation were by no means extreme in terms of climatic conditions. The experimental results clearly confirm, however, that total rainfall by itself cannot be used as an indicator of yield, especially grain yield. Besides, drier years may result in greater WUE and partial factor productivity of N, P and K.

In both years of the experiment, millet responded positively to even modest amounts of manure and fertilizer applications (in the range of 0-50 kg N ha^{-1} and 0-13 kg P ha^{-1}), despite the contrasted rainfall conditions. This is in agreement with previous results and reflects the low native fertility of the soils. According to Bationo and Buerkert (2001), modest quantities of manure and fertilizers frequently double or even triple grain yields in most years. For example, Rockstrom and De Rouw (1997) found that small quantities, 25 or 50 kg ha^{-1} of N and 10 kg ha^{-1} of P buried next to individual pockets, were sufficient to double or triple the grain yields in normal rainfall years. The lack of impact of residue application on millet yields in 1994 may result from the late application of the residue (Table 4.1). Early application of residue during the dry season may lead to partial decomposition (e.g., through termites) and a faster release of nutrients and organic compounds during the rainy season, with a stronger positive effect on soil pH and P availability (Hafner *et al.*, 1993b; Rebafka *et al.*, 1994). In addition, Buerkert and Stern (1995) reported that millet responded positively to residue application on low productivity plots whereas little response was observed on high productivity plots. Given that the experimental field had only been cultivated for one year prior to the experiment following a long term fallow period, the overall level of productivity of the field was probably higher in 1994 than in 1995. Hence a proportionally stronger response to residue application may be expected in 1995 than in 1994.

There was no interaction between any of the treatments in 1994 regarding stover and grain yields. In 1995, a significant interaction was observed between residue and fertilizer with respect to grain and stover yields, but also with respect to WUE and partial factor productivity of N and P. At medium (900R) and high (2700R) levels of CR, the response to fertilization was strong, with yields and WUE more than doubling following the application of 45N15P compared to the control (0N0P). At low levels of crop residue (300R), the response to fertilizer was about half of the response at the two highest rates of CR application. In addition, the decrease in the PFP of N and P in response to fertilization was strongest at the lowest level of crop residue (300R) whereas it tended to remain constant at the highest rate of residue (2700R), indicating that for 2700R, the yield increase resulting from the application of 45N13P was approx. proportional to the amount of N and P added, which was not the case at lower levels of residue (Figure 4.7). Albeit not significant, a similar residue x fertilizer interaction was observed in 1994 (not shown). Few experiments have reported on the response of millet to low levels of CR. However, the rapid acidification of the soil in the absence of residue restitution is well documented (e.g. Bielders *et al.*, 2002; Buerkert and Lamers, 1999). In the present case, it may be that fertilizer application resulted in some acidification of the soil for the 300R treatment, with, among others, negative consequences on P availability. It is unlikely that K became limiting at high combined rates of manure and fertilizer. Indeed, neglecting K losses through leaching and wind erosion and K additions through dust deposition, the nutrient balance for the 300R-2700M-45N13P treatment was positive in both years (Table 4.9). This is because the manure supplied large quantities of K (Table 4.2). At high rates of fertilizers (45N13P) but low rates of residue and manure, K balances were negative in both years, such that K deficiency may develop (Table 4.9). Rebafka *et al.* (1994) have reported large responses to K fertilizer in the absence of crop residue restitution. Voortman and Brouwer (2003) also highlighted the importance of K in explaining spatial variability of crop growth.

The response to N (Figure 4.7) and P (not shown) supplied by manure and fertilizer appear fairly consistent and additive (Table 4.4), but only up to a certain application rate of N and P. Indeed, in 1995, there was a significant Fert x Man interaction. Combining the highest rates of manure and fertilizer resulted in no further increase or even a decrease in millet yields (Figure 4.3). Although not statistically significant, a similar Fert x Man interaction was observed in 1994 (not shown). This may reflect the fact that yields were limited by factors other than N or P fertilization under the soil and climatic conditions of the experiment. Figure 4.9 shows the average (over all residue application rates) response of millet stover (Figure 4.9a) and grain (Figure 4.9b) to N application from manure and fertilizer in 1994 and 1995. Although stover yields are lower on average in 1995, the graph indicates that maximum stover yields could have been expected in both years at combined application rates of the order of 40-60 kg N, realizing that P and K were also applied in all treatments. A similar graph can be drawn with respect to P (not shown). Christianson *et al.* (1990) reported nitrogen response curves averaged over different sources of inorganic N and for different mid-season (16 July - 31 August) rainfall amounts. Mid-season rainfall for 1994 and 1995 was 411 and 230 mm, respectively. The response curves proposed by these authors are drawn in Figure 4.9. Regarding stover yield, the shape of the N response curve for 1994 is consistent with the present study, albeit translated to higher yields. For 1995, the maximum stover yield is achieved at lower N rates than observed in the present study. Regarding grain yield, observed and predicted curves are rather different. Maximum predicted yields occur at lower N rates than found in the present study. In addition, the regression model of Christianson *et al.* (1990) predicts higher grain yields in 1994 rather than 1995, contrary to the observed response. One must

Table 4.9. Millet yield, water use efficiency (WUE), partial factor productivity (PFP) of N, P and K, and N, P, K balances for three selected treatments suitable for recommendation based on the experiment conducted at ICRISAT Sahelian center, 1994-1995.

		300R-2700M-0N0P		900R-2700M-0N0P		900R-2700M-15N4P	
Factor	Units	1994	1995	1994	1995	1994	1995
Grain yield	kg ha^{-1}	722	613	493	658	813	891
Straw yield	kg ha^{-1}	1754	1077	1315	1056	2207	1458
WUE	kg ha^{-1} mm^{-1}	1.56	2.14	1.05	2.28	1.77	3.34
PFP N	kg grain kg^{-1} N	25	21	14	20	17	18
PFP P	kg grain kg^{-1} P	130	110	84	112	79	87
PFP K	kg grain kg^{-1} K	14	12	8	10	12	14
N bal	kg ha^{-1}	-2.0	12.0	12.3	17.0	10.7	25.3
P bal	kg ha^{-1}	1.3	3.3	3.3	3.3	5.0	7
K bal	kg ha^{-1}	0.3	20.7	26.0	30.0	7.0	20.7

*, **, *** probability significant at 0.05, 0.01, 0.001 respectively.

not forget, however, that the mid-season rainfall of 1994 falls outside the validation range of the Christianson *et al.* (1990) study. It is therefore likely that the probably high leaching losses of N in 1994 are not properly taken into account by Christianson *et al.* (1990)'s study. In addition, these authors did not include organic sources of N.

The low observed impact of increased millet productivity on ET is due to the fact that even at high fertility levels and densities around 10000 pockets ha^{-1}, vegetation remains sparse for most of the season in the Sahel and LAI seldom exceeds 1 to 1.5 m^2 m^{-2} (Azam-Ali *et al.*, 1984). Although greater above ground biomass will result in greater LAI and larger transpiration losses, these losses are largely compensated for by a reduction in soil evaporation. Payne (1997) also found that higher biomass yields resulting from high rates of fertilization hardly increased ET in the Sahel and, consequently, WUE is mostly influenced by changes in crop yield in response to the soil nutrient status or fertility management strategies (Hatfield *et al.*, 2001; Bielders and Michels, 2002). This highlights once more the need to improve soil fertility in order to achieve greater WUE in millet-based rainfed systems.

4.4.2 Recommendations

No third level (residue x manure x fertilizer) interaction was generally observed. Wang *et al.* (2007) also found no such interaction in a similar INM and long term experiment on maize grain yield, N, P and K uptakes under reduced tillage in northern China. But they pointed out that added manure and stover were more important especially for dry years and NP fertilizer for wet years because the annual rainfall and soil water condition at sowing played a major role contrary to the Sahelian environment. Hence our experiment did not reveal any treatment combinations that could be viewed as particularly favorable or unfavorable. However, a number of recommendations can be drawn from the experiment. Although high rates of residue had no adverse effects and a positive response to residue was observed in 1995, for technical reasons the highest rate of residue (2700R) cannot be recommended in practice as the production of the mulching material cannot be sustained. Hence only treatment combinations involving 300R or 900R should be considered for practical applications. Maintaining a positive nutrient balance is an essential requirement of INM. At residue rates of 300 kg ha^{-1}, positive balances were obtained in both years only for the highest rate of manure (2700M; Table 4.9). This is required in particular to sustain the K balance, in the absence of K fertilization, as the manure supplied large quantities of K. A viable option would therefore be to combine low levels of residue (300R) as observed at the end of the dry season in most fields, with 2700 kg ha^{-1} of manure. With a supply of 27 kg N ha^{-1}, this treatment combination results in a 95% increase in yields on average over the two years (Figure 4.9). Given the poor response of millet to fertilizer at low rates of residue (300R; res x fert interaction, Table 4.6), these treatment combinations cannot be recommended. All treatment combinations involving 900R and 2700M presented a positive nutrient balance in both years (Table 4.9) and may therefore be considered in practice. The combination of high rates of manure (2700M) and fertilizer (45N13P) should not be recommended, however, given the Man x Fert interaction observed in 1995 (Table 4.6) and the shape of the yield response curves (Figure 4.9). Hence, besides the 300R-2700M-0N0P, the 0N0P or 15N4P fertilization in combination with

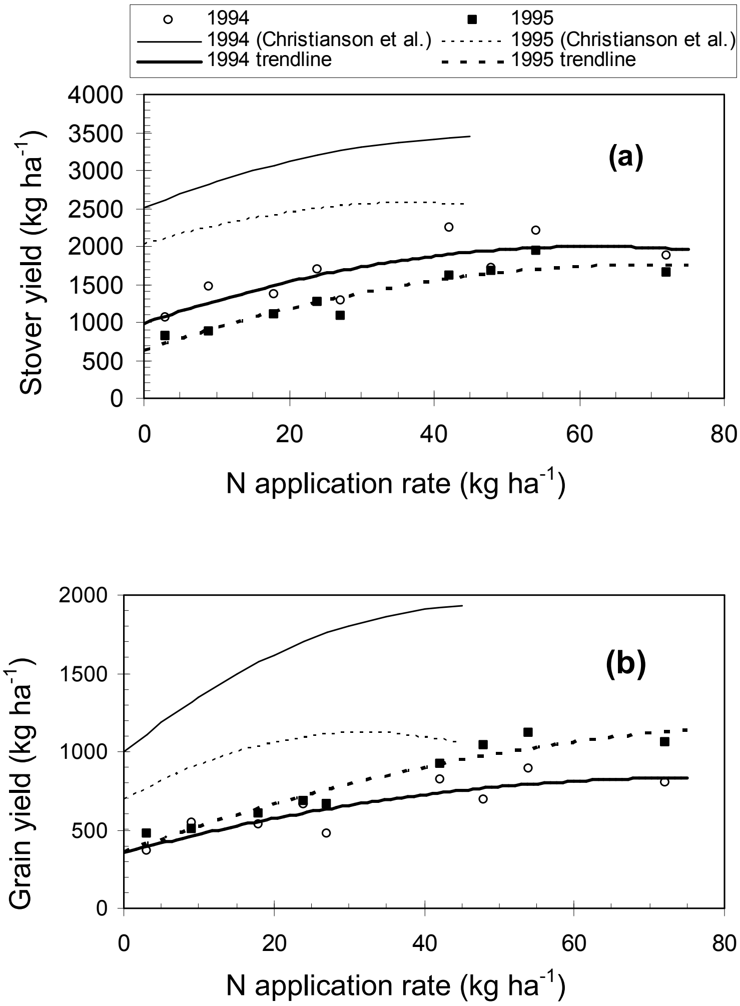

Figure 4.9. Millet stover (a) and grain (b) yield response to N input from combined application of cattle manure and mineral fertilizer in 1994 and 1995 at ICRISAT Sahelian center, Sadoré, Niger. Measured yields (dots and trendlines) are averaged over all residue application rates and are compared to data from Christianson et al. (1990).

2700M and 900 R could be retained in practice. Table 4.9 provides an overview of the various agronomic criteria for the three selected treatments. On that basis, it appears that the 900R-2700M-0N0P offers no advantages over the 300R-2700M-0N0P. On the basis of the agronomic criteria used here and depending on socio-economic factors (access to manure and fertilizer, cost of fertilizer or manure, opportunity cost for crop residue, etc.), one would therefore recommend the 300R-2700M-0N0P or 900R-2700M-15N4P treatments. These results would need to be confirmed through longer term experiments and may have to be refined on the basis of complete nutrient balances. Indeed, the present balances, though easy to perform, neglect a number of inputs and outputs (leaching, atmospheric deposition, N fixation, volatilization, etc..). For CAN for instance, Christianson *et al.* (1990) reported losses of the order of 25 to 37%. The recommendations derived here should not be considered as mutually exclusive but may be implemented differentially depending on site specific differences in productivity (Voortman and Brouwer, 2003).

4.5 Conclusions

The beneficial effects of combined organic and inorganic nutrients sources on soil fertility have been repeatedly claimed, yet no previous experiments have dealt with the combined management of residues, manure and inorganic fertilizers and hence no guidelines are available for their combined management (Palm *et al.*, 1997). This study revealed some additive effects of the three tested amendments and some positive synergetic effects. The main additive effect concerns manure and crop residue application in both years (i.e., no residue x manure interaction). A synergetic effect between residue and fertilizer was revealed in 1995 for stover and grain yields and for PFP of N and P and for PFP of N, P and K in 1994. It appeared that high rates of fertilizer should not be combined with low rates of crop residue. This may have to do with soil acidification and poor P mobilization in the absence of soluble organic compounds derived from residue decomposition. The highest rates of manure (2700 kg ha^{-1}) and fertilizer (45N13P) should also not be combined as this leads to no additional yield increase or even to a yield decrease. At lower rates (up to 50 kg N ha^{-1}), the effects of manure and fertilizer seemed to be largely equivalent, leading to a consistent yield response, yet one should not forget that manure constitutes a major supply of K (and other micronutrients) as well. There was no third order interaction between residue, manure and fertilizers except for PFP of N in 1995.

Two treatments stand out as particularly relevant in practice based on yield, WUE, partial factor productivity and nutrient balance criteria. A combination of 300 kg ha^{-1} of millet residue and 2700 kg ha^{-1} of manure without fertilizer would be appropriate in case of poor access to fertilizer (for availability or cost reasons) and results in a 95% yield increase. A higher input combination of 900 kg ha^{-1} millet residue, 2700 kg ha^{-1} manure and 15 kg N + 4 kg P ha^{-1} as fertilizer would lead to an average increase in grain yield of 132%. In this treatment, the higher rate of residue application seems essential to counteract any acidification that may result from the use of inorganic fertilizers, as well as to provide K and enhance P mobilization. These results would need to be confirmed through longer term experiments and may have to be refined on the basis of comprehensive nutrient balances.

Chapter 5

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

Abstract

Soil fertility and climate risks are hampering crop production in the Sahelian region. Because field 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 relations, crop growth simulation models could suitably complement experimental research to support decision making regarding soil fertility and water management. This paper reports on the long term (23 years) simulation of millet response to N in a factorial numerical experiment in support of a better adapted recommendations to subsistence small-holder millet farming in the Sahel. Prior to this, the Agricultural Production Systems Simulator (APSIM) model was tested on a rainfed randomized complete block experiment. The experiment combined at three levels each, application of cattle manure (300, 900 and 2700 kg ha^{-1}), millet residue

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- Akponikpè, P.B.I., Bielders, C.L., Gérard, B., Michels, K., 2007. Modelling integrated fertility management strategies for pearl millet in the Sahel. De Neve, S., Salomez, J, Van Bossche, A., Haneklaus, S., Van Cleemput, O., Hofman, G., and Schnug, E. Eds. "Mineral versus organic fertilization: conflict or synergism ?" Proceedings of the 16th international symposium of the International Scientific Centre for Fertilizers (CIEC). 2007. Gent, Belgium, CIEC

(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 during the 1994 and 1995 cropping seasons having contrasted rainfall conditions. 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 testing experiment. APSIM simulations were in satisfactory agreement with the observed crop growth (LAI, biomass) except for the highest crop residue application rates. 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 factorial numerical experiment 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 at 30 kg N ha^{-1}, the application of 15 kg N ha^{-1} appears more appropriate for smallholder, subsistence farmers than the usual 30 kg N ha^{-1} recommendation in as far as it guarantees higher minimum yield in extreme dry years, thereby reducing their vulnerability. Our finds should be considered in conditions where P is added proportionally to N (P/N in the range of 20 to 30%).

Keywords: APSIM, fertilizer, manure, modeling, pearl millet, residue, Sahel.

5.1 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.*, 1993b; 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 over a limited number of years (Bationo *et al.*, 1992). However, it is well known that millet response to N is strongly dependent on climatic conditions, mostly the amount and temporal distribution of rainfall and the availability of other nutrients such as P (Gandah *et al.*, 2003a). 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, Akponikpè *et al.* (2008, Chapter 4)) have shown that these relationships do not necessarily hold for other years, experimental conditions and organic sources of N. Substantial literature also exists regarding the fact that the 30 kg N ha^{-1} recommendation presents a high economic risk for smallholder 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. Current N recommendations have clearly not been derived from 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 N management strategies, among which 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 (Hafner *et al.*, 1993a; Rebafka *et al.*, 1994). This latter approach is, however, extremely costly and such experiments are extremely rare in the Sahelian region. To lift this limitation, shorter 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 for 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. They found that these models were more appropriate to predict the influence of drought under decreasing rainfall conditions than existing empirical models. SARRAH, a crop model simulating attainable yield under optimal soil fertility condition was used to analyze the impact of regional climatic variability on millet yield (Sultan *et al.*, 2005a) 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 models capable of dealing with water and N dynamics and simulate various fertility management options (mineral and organic amendments). In addition APSIM has recently been complemented with a specific millet tillering module 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.*, 2001a, 2002). The model could adequately predict biomass, grain yield, and LAI. For all the above mentioned reasons, APSIM appears highly suitable for modeling millet response to climate and soil fertility management in the Sahelian environment. However, a necessary prerequisite is to confirm the suitability of the model through a proper calibration and validation for Sahelian millet cultivar(s) and agro-climatic conditions. Parameterisation of the APSIM model for common millet landraces and improved cultivars of Niger was described in chapter 3. The main objective of this paper is therefore to calibrate and validate the performance of the APSIM model in terms of millet response to climatic conditions under 3 main fertility management practices: manure, crop residue and fertilizer. The model is subsequently used to simulate millet response to N over the long term (23 years) in a factorial numerical experiment in order to arrive at recommendations better adapted to subsistence small-holder millet farming in the Sahel.

5.2 Materials and methods

5.2.1 Experimental data

This research capitalizes on past on station data (experiment I and III) and a recent experiment (experiment II). All the experiments took place during the normal millet cropping season at Sadoré, Niger (13°15'N, 2°17'E and 240 m of altitude) 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 a bare plot experiment (no millet or other crop and regularly weeded) to study water balance in the absence of any crop. It took place during the rainy season between 28 May 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 x 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.

Experiment II. Because default parameterization of the APSIM millet module using Indian cultivars lead to completely unsatisfactory results, an experiment was conducted to characterize the Nigerien millet cultivar CIVT (Composite Inter-Varietal de Tarna, early maturing, 95 days approximately). It 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. This experiment is thoroughly presented in chapter 3.

Experiment III was conducted during the 1994 and 1995 rainy seasons at Sadoré. The objective was to evaluate the effect of combined application of cattle manure, millet residues and mineral fertilizer on pearl millet production in the Sahel. Details of this experiment are reported elsewhere (Akponikpè *et al.*, 2008, Chapter 4). The experimental design consisted in 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 (unfertilized control, 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 was sown in hills without prior tillage after the first sufficient rainfall event (>20 mm) in each year, at a density of 12500 and 10000 hills ha^{-1} thinned to 2 and 3 plants hill^{-1}, respectively in 1994 and 1995. Millet was sown on 6 June 1994 and 20 June 1995 and harvested on 20-23 September 1994 and 26-27 September 1995. Above ground biomass and LAI were measured by destructive sampling several times during the season in 1994 but not in 1995. Plant available water (PAW) was computed from neutron probe water content profile measurements made every two weeks in all plots. Final biomass and grain yield were measured both years.

5.2.2 Model description, inputs and parameterization

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). Five modules, a specific crop module (APSIM-millet 3.6), a soil water module (Soilwat2), the soil nitrogen module (Soiln2), the residue module (Residue2), 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 and management (planting, organic matter or fertilizer application). Model parameterization is described hereunder. Additional parameters are provided in Table 5.1.

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

Drained upper limit water content at field capacity (*dul*), drainage rate between soil layers at water content > *dul* (*swcon*, considered equal for all depths), the first and second stage soil evaporation coefficients *u* and *cona* were calibrated against data from experiment I. Calibration was based on PAW measurement of experiment I and was performed by optimization using the nonlinear parameter estimation package PEST® (Doherty, 2004) between appropriate intervals of *swcon* (0.01 - 1), u (0.01 - 40 mm), *cona* (0.01 - 10) and *dul* (0 - 0.4). The bare soil runoff curve number (*cn2_bare*) was set to 50 to account for the fact that runoff was very low because of the flat topography and high infiltration rates due to the sandy soil characteristic of the experimental site. Parameterization of lower limit water content at 15 bar matric pressure (*ll15*), bulk density (*bd*), organic carbon content (OC), initial NH4-H and NO3-N and pH was done using published data or measurements during experiment III (Table 5.2).

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,

Table 5.1. Input data required for APSIM standard simulation model

Parameter or variables	Acronym	Value	Units
Phenology			
Sowing - Germination	-	PAW > 0.0[a]	mm mm^{-1}
Germination - Emergence	-	10.7+1.17 x SwD[b]	°C days
Emergence - end juvenile	tt_emerg_to_endjuv	483	°C days
End-juvenile - Floral initiation	-	112x(photoperiod-13.4) 46 x leaf number	°C days
Emergence - Flag leaf	-	46 x 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	
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	50	-
Reduction in cn2_bare due to cover	cn_red	28	-
Each 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 next Table when variable

Table 5.2. Soil physical and chemical model inputs for the experimental field at ICRISAT Sahelian center, Sadoré. 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	ll15[a]	dul[b]	sat[c]	bd[a]	NO3-N[a]	NH4-N[a]	OC[d]	pH_{H20}[d]
[m]	——[m^3 m^{-3}]——			[Mg m^{-3}]	——[mg m^{-3}]——		%	[-]
0-0.05	0.02	0.07	0.33	1.65	6.00	0.50	0.19	5.40
0.05-0.1	0.03	0.07	0.37	1.55	6.00	0.50	0.19	5.60
0.1-0.2	0.03	0.07	0.37	1.54	6.00	0.50	0.19	5.60
0.2-0.3	0.03	0.07	0.39	1.48	6.00	0.50	0.13	5.70
0.3-0.4	0.04	0.07	0.35	1.59	0.10	0.10	0.13	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	0.10	0.10	0.09	5.20
0.7-1.0	0.04	0.07	0.34	1.62	0.10	0.10	0.08	5.20
1.0-2.0	0.04	0.07	0.34	1.61	0.10	0.10	0.08	5.20

[a]from Fechter (1993)
[b]Calibrated with PEST® (Doherty, 2004)
[c]Calculated as sat = 1 - (bd / 2.65) - 0.05
[d]from experiment III

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 in soil restricts decomposition of residues. Millet residue and manure chemical composition needed in the model were measured and taken from experiment III. Potential decomposition rates were obtained from the literature (Table 5.1) (Esse *et al.*, 2001; Fatondji, 2002).

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 (see Appendix for a full description). Pearl millet growth responds to climate (temperature, rainfall, radiation, photoperiod), soil water supply (from soilwat2 module), and soil nitrogen (from 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 5.1). 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, 1983a; Van Oosterom *et al.*, 2001a). Between the stage of emergence and flag leaf appearance, the calculated daily thermal time is reduced by water or nitrogen stresses, 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.

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 5.1). Required leaf area parameters (regression coefficients of the area of the largest leaf on total leaf number) were also derived from this experiment (Table 5.1, chapter 3).

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. Parameter optimization with PEST® of *ll*, *kl*, *rue*, transpiration efficiency coefficient (*transp_eff_cf*), grain growth rate (*grain_gth_rate*), maximum head grain number (*head_grain_no_max*) using grain yield observations for some selected treatments of experiment III did not result in significantly better simulation results than those obtained using default parameter values. Default parameters were therefore retained.

5.2.3 Model evaluation and sensitivity analysis

Model evaluation The evaluation (examining and comparing measured and simulated values) was performed on the 27 treatments and the two-year data of experiment III with respect to PAW (1994-1995), above ground biomass (1994) and final biomass and grain yield (1994-1995). Given that none of the model parameters had been adjusted on the basis of experiment III, the model performance evaluation can be considered as a true validation. Simulation outputs were analyzed by both statistical criteria and graphical representations (Loague and Green, 1991). The statistical criteria are based on the analysis of residual errors, i.e. the difference between observed and simulated values. We computed the root mean square error RMSE, the square of the correlation coefficient R^2, and the model efficiency EF (details in chapter 3). One would expect to have values of RMSE, R^2 and EF as close as possible to 0, 1 and 1, respectively. RMSE, R^2 and EF 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.

Sensitivity analysis A sensitivity analysis of grain yield was carried out for 1994 and 1995 by considering changes (-75, -50, -25, -10, 0, +10, +25, +50 and +75%) of selected parameters. This was done for the two extreme treatments of experiment III: the lowest (R1F1M1) and highest (R3F3M3) fertilized treatments. Parameters considered were: i) soil water balance related parameters (*swcon*, *cn2_bare, cn_red*, *cona*, *u*, *kl* and millet *ll*), ii) soil chemical parameters (OC, pH, initial ammonium-N (*nh4ppm*), initial nitrate-N (*no3ppm*), initial inert fraction of organic carbon (*finert*), initial non-inert fraction of carbon in microbial biomass (*fbiom*), soil C/N ratio (*soil_cn*), time constant for millet N uptake by diffusion (*no3_diff_const*) and iii) growth related parameters (*rue*, *transp_eff_cf*, *head_grain_no_max* and *grain_gth_rate*). Only one parameter was varied at a time and interaction between parameters was not evaluated. Chemical parameters were not reinitialized for the 1995 simulation to account for the residual effects of the 1994 amendment applications. The changes in the selected parameters were programmed in a compter code with the Python language (van Rossum, 2006) which calls the APSIM model to run each case of the sensitivity analysis.

5.2.4 Long-term factorial experiment simulation

The calibrated and validated APSIM model was used to simulate a 6 x 6 x 2 factorial numerical experiment combining manure at 6 levels (0 to 2500 kg ha^{-1} with 500 kg ha^{-1} increment), N fertilizer as CAN at 6 levels (0 to 50 kg N ha^{-1} with 10 kg N ha^{-1} increment) and millet residue at 2 levels (0 and 500 kg ha^{-1}) over a period of 23 years (1983 to 2005) using daily agro-climatic data (rainfall, minimum and maximum temperature, solar radiation, relative humidity) from the ICRISAT research station at Sadoré. Initial soil chemical parameters were reset at each year simulation. Crop residue application rates $>$ 500 kg ha^{-1} were not simulated as model response to such levels of residue proved not to be suitable. Rainfall characteristics of the simulation period are presented in Figure 5.13. During each simulation year millet sowing was allowed when a total rainfall over 15 mm occurred over three consecutive days between May 1st 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. Resowing of millet in case of crop failure is frequently practiced by farmers in the area. 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}. Total amount (depending of simulation level) of manure or residue was applied on May 1st every year. For N fertilizer, application rate was split into 2: the first (0 to 30 kg N ha^{-1}) on the 1st day after sowing (DAS) and the remaining at 50 DAS. We programmed the factorial numerical experiment in a compter code with the Python language (van Rossum, 2006) which calls the APSIM model to run each treatment (72) for a given year (23).

5.3 Results

5.3.1 Rainfall, temperature and solar radiation during experiment III

Rainfall during the cropping period was 721 mm in 1994 and 431 mm in 1995, whereas for the whole year it was 794 mm in 1994 and 486 mm in 1995 (Figure 5.1). 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 contrasted rainfall conditions make these two years very relevant for testing the model in terms of millet response to fertility management options in the Sahel.

5.3.2 Calibration of soil water related parameters (Exp. I)

The best calibration was obtained with the following set of parameters: *swcon* (0.41), *cona* (0.01), *dul* (0.07 m^3 m^{-3}) and *u* (8.65 mm). RMSE and R^2 were 9 mm and 0.88, respectively, for PAW (Figure 5.2). Simulated PAW matched well with observations during the entire calibration experiment.

5.3.3 Evaluation of PAW (Exp. III)

The range of PAW RMSE values 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 to 1.8% over the entire rooting depth (0-1.50 m). Model performance was satisfactory in simulating PAW (Figure 5.3 a to f). Model efficiency EF, calculated for each individual treatment, ranged from -0.3 to 0.6 in 1994 and -1.5 to 0.6 in 1995 with more than 70% of treatments having EF $>$ 0 in both years (Figure 5.4).

5.3.4 Millet growth and yield evaluation

Simulated soil water and nitrogen stress for photosynthesis 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 (Figure 5.5). 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.

Evolution of total biomass above ground The evolution of total above ground biomass during the 1994 growing season was used to assess millet growth. RMSE ranged from 144 to 1568 kg ha^{-1} for the 27 treatments. 80% of RMSE values are below 600 kg ha^{-1} (Figure 5.4). Model efficiency ranged from 0.5 to 1.0 with 80% of the treatments having EF $>$ 0.75. APSIM simulations were in satisfactory agreement with the observed biomass over time (Figure 5.6). Nevertheless high observed biomass values tended to be underestimated by the model (Figure 5.6a, b). It was found 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 (Figure 5.6a).

Evolution of leaf area index (LAI) RMSE of LAI ranged from 0.07 to 0.43 m^2 m^{-2} over the 27 treatments in 1994. 90% of RMSE values were below 0.25 m^2 m^{-2} (Figure 5.4). Model efficiency EF ranged from -1.1 to 1.0 with 70% of treatment EF values over 0.5 m^2 m^{-2}. Despite an overall satisfactory response of the APSIM simulation model with regard to LAI, high observed LAI values from the R3

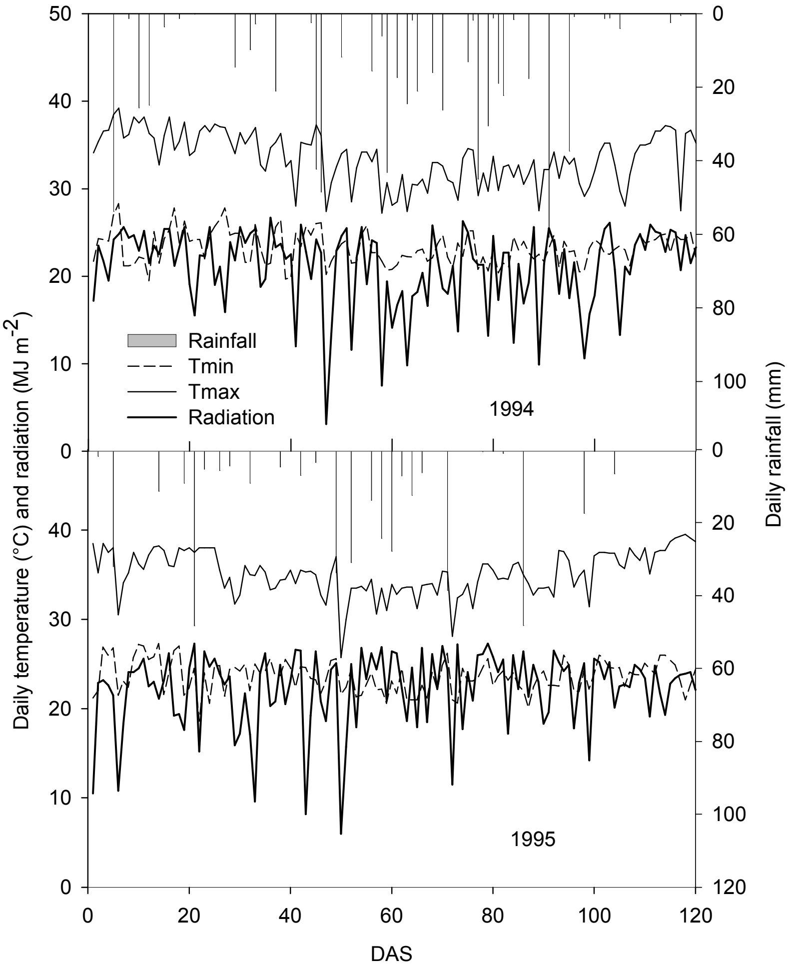


Figure 5.1. Daily rainfall, minimum (Tmin) and maximum (Tmax) temperatures and solar radiation at Sadoré, Niger during experiment III in 1994 and 1995.

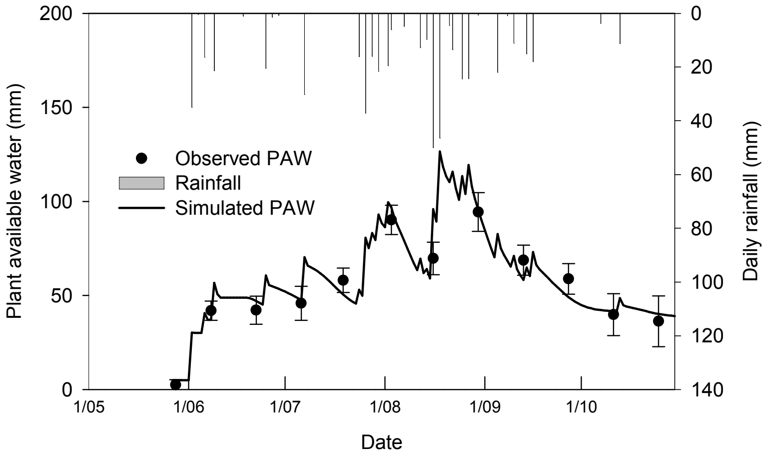


Figure 5.2. Simulated versus observed plant available water PAW in 0-150 cm depth following soil water parameter calibration with PEST® (Experiment I, 1996). Error bars denote standard deviation of measurements, n=30.

Table 5.3. Root mean square error (RMSE), linear correlation coefficient (R^2) and modeling efficiency (EF) of modeled 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, Sadoré, 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)
R^2	0.56 (0.59)	0.51 (0.53)	0.55 (0.63)	0.53 (0.55)
EF	0.39 (0.35)	-1.50 (-2.49)	0.01 (0.03)	0.39 (0.52)

treatments tended to be underestimated by the model (Figure 5.7d). Removing data of these treatments improved the model performance (Figure 5.7b).

Biomass and grain yields and crop response to N Model performance differed between the two years of experiment III. For total above ground biomass at harvest, the RMSE was 615 and 1294 kg ha^{-1} in 1994 and 1995, respectively. R^2 was 0.56 and 0.51 for these two years, respectively (Table 5.3). APSIM model performance was relatively good in 1994 but biomass yield was slightly overpredicted in 1995 (Figure 5.8a)

The APSIM model performed also well in terms of grain yield response to fertilizer, manure and crop residue application (Figure 5.8b). The RMSE was 206 kg ha^{-1} in 1994 and 1995. R^2 was 0.55 and 0.53 for the same two years, respectively. Model efficiency was 0.01, and 0.39 in 1994 and 1995, respectively (Table 5 3). Experimental, within-treatment standard deviations for both total biomass and grain yield

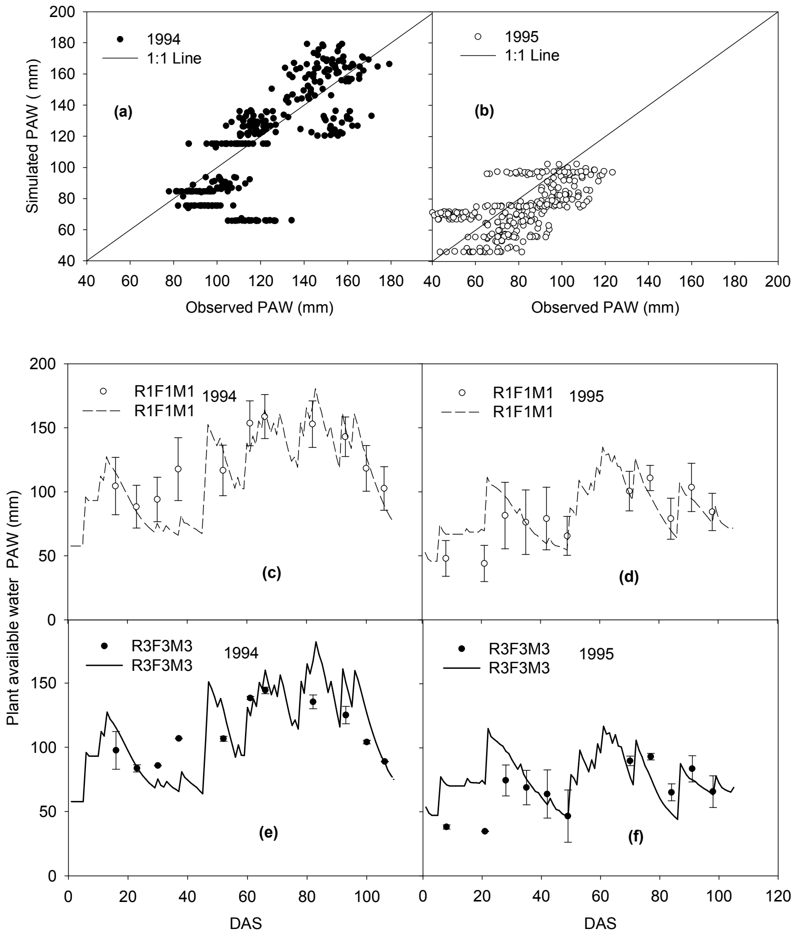


Figure 5.3. Comparison between (a, b) observed and APSIM simulated plant available water PAW (0-150 cm) for all 27 treatments (11 dates per treatment in experiment III) and (c, d, e, f) details for selected treatments of combined application of cattle manure, crop residue and mineral fertilizer in 1994 and 1995 at ICRISAT Sahelian center, Sadoré, Niger. Dots and lines are respectively observed and simulated values in (c, d, e, f). Error bars denote standard deviation of measurements, n=3.

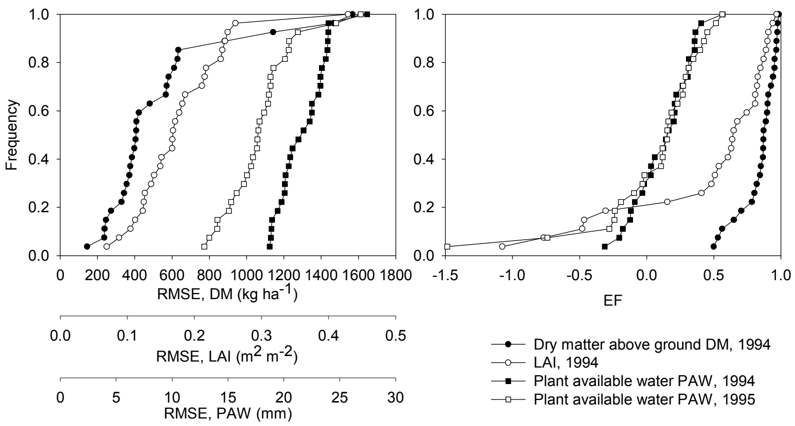


Figure 5.4. Performance of APSIM in simulating the evolution of plant available water (PAW;0-1.50 m), LAI and millet above ground dry matter (DM) in experiment III for the 27 combinations of cattle manure, crop residue and mineral fertilizer application in 1994 and 1995 at ICRISAT Sahelian center, Sadoré, Niger. Each dot corresponds to the seasonal RMSE or EF of a given treatment (n= 27).

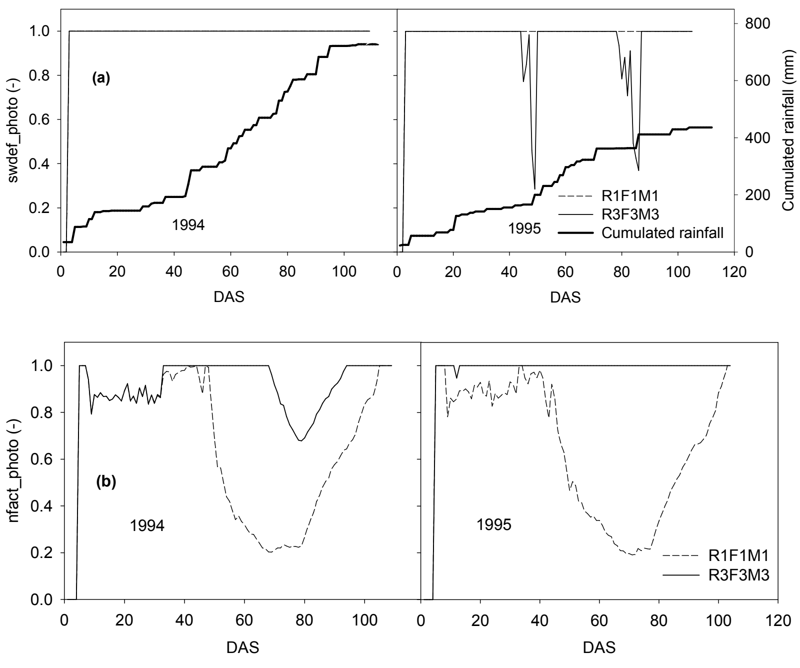


Figure 5.5. Cumulative rainfall and simulated soil water deficit factor for photosynthesis (swdef_photo) and nitrogen deficit factor (nfact_photo) for selected treatments in experiment III combining application of cattle manure, crop residue and mineral fertilizer in 1994 and 1995 at ICRISAT Sahelian center, Sadoré, Niger.

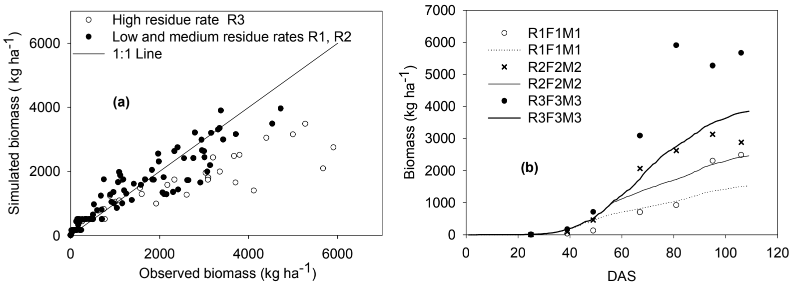


Figure 5.6. Comparison between observed and APSIM simulated millet temporal above ground biomass for (a) all 27 treatments (7 dates per treatment; experiment III) and all treatments except those with R3 (2700 kg residue ha^{-1}), and (b) three selected treatments of combined application of cattle manure (M), crop residue (R) and mineral fertilizer (F) in 1994 at ICRISAT Sahelian center, Sadoré, Niger. Dots and lines are respectively observed and simulated values.

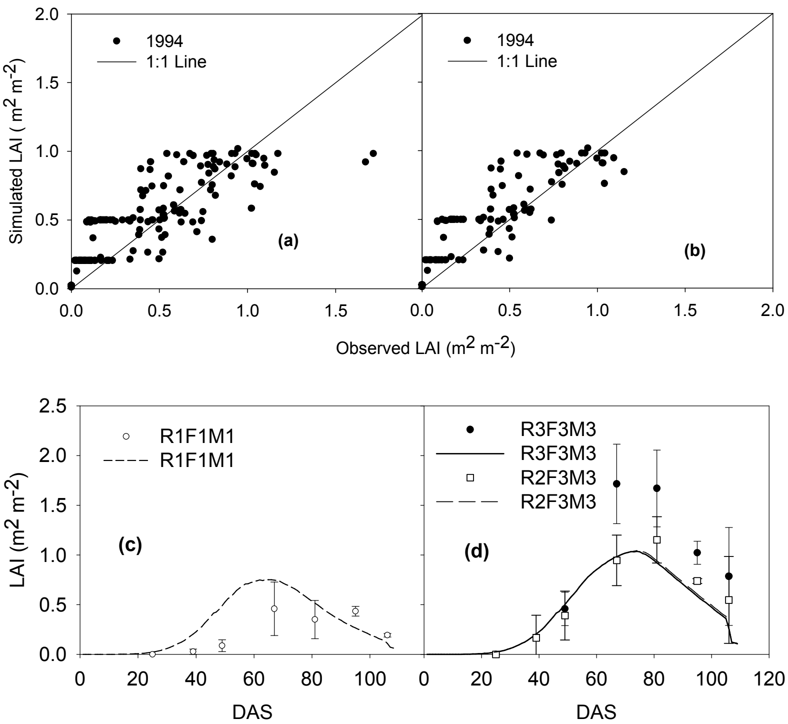
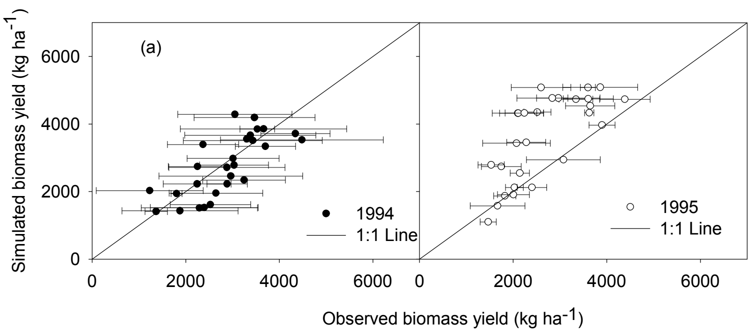


Figure 5.7. Comparison between observed and APSIM simulated millet LAI for (a) 27 all treatments (7 dates per treatment) (b) all treatments except those with R3 (2700 kg ha^{-1}) and (c, d) three selected treatments as affected by combined application of cattle manure, crop residue and mineral fertilizer in 1994 at ICRISAT Sahelian center, Sadoré, Niger. Dots and lines are respectively observed and simulated values in (c, d). Error bars denote standard deviation of measurement. Error bars denote standard deviation of measurement, n=3.



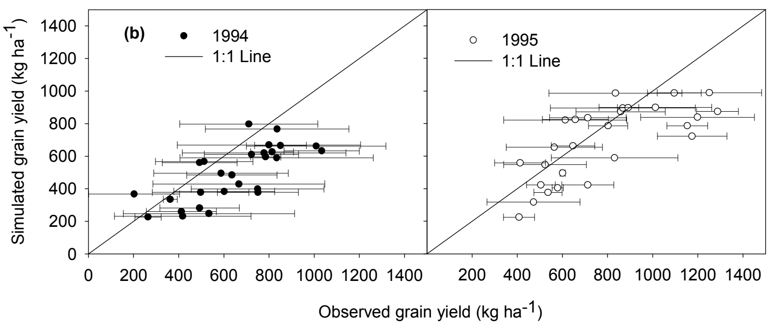


Figure 5.8. Comparison between observed and APSIM simulated millet biomass (a) and grain (b) yield as affected by combined application of cattle manure, crop residue and mineral fertilizer in 1994 and 1995 at ICRISAT Sahelian center, Sadoré, Niger. Error bars denote standard deviation of observed means, n=3.

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 deviation of the observed values (Figure 5.8). In the same way the R3 treatments were found to depreciate the model performance of the model in simulating the time course of biomass, the performance in terms of total biomass and grain yield was generally improved by removing these treatments (Table 5.3).

The model reproduced well the average trend of millet grain yield response to N inputs (Figure 5.9). It was able to adequately reproduce the overall higher observed grain yield in 1995 compared to 1994, despite the better rainfall in 1994.

5.3.5 Sensitivity analysis

Water balance parameters Variation of *cn_red* and *cona* resulted in limited change of grain yield (Figure 5.10). Grain yield was the most sensitive to variation in *swcon* and to a lesser extent to *cn2_bare*, *u*, *kl* and *ll*. However, the sensitivity

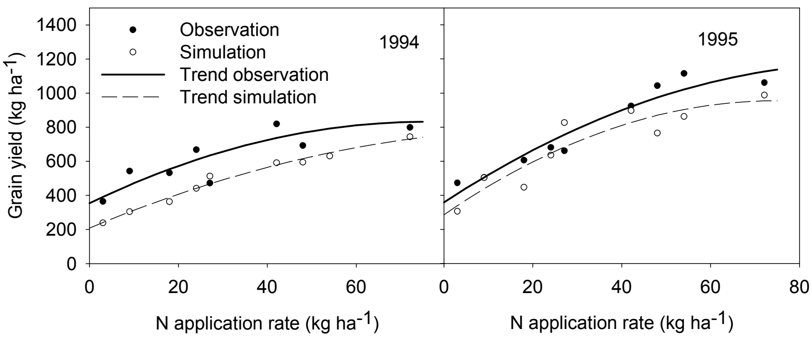


Figure 5.9. Observed and simulated millet grain yield response to N inputs from combined application of cattle manure and mineral fertilizer in 1994 and 1995 at ICRISAT Sahelian center, Sadoré, Niger. Measured yields are averaged over all residue application rates. Trendlines are second order polynomials.

depends on year and treatment. *Cn2_bare* determines the rainfall partitioning into infiltration and runoff whereas swcon determines the rate of drainage of layers having water content greater than dul. Increasing *cn2_bare* increased substantially grain yield in 1994 for the lowest fertilized treatment R1F1M1 contrary to the highest fertilized R3F3M3. This is a consequence of a diminished nitrate leaching produced by reduced infiltration during the heavy and frequent rainfalls of this year. Grain yield decreased almost linearly with increased *swcon* in the R1F1M1 treatment in 1994. Increasing *swcon* results in increased N leaching that affects more strongly the N-poor treatment mainly during wet year of 1994 (Figure 5.5b). In 1995 only, grain yield was sensitive to *kl* in the case of treatment R3F3M3 whereas the sensitivity to *ll* was observed for both treatments (R1F1M1 and R3F3M3). Diminishing *kl* or increasing *ll* results in decreased grain yield because these changes reduce water availability which was limiting mainly in the drier year (1995) and more strongly in the case of the higher fertilized treatments (Figure 5.5a).

Soil chemical parameters Grain yield was not sensitive to any of the soil chemical parameters for the highest fertilized treatment R3F3M3 either in 1994 or in 1995 (Figure 5.11). The heavy fertilizer application in treatment R3F3M3 was enough to mask the effect of the initial soil properties. In contrast grain yield of the lowest fertilized treatment R1F1M1 was very sensitive to changes of *finert*, *soil_cn*, *OC* parameters with a greater effect in 1995. Increasing *finert* or *soil_cn* results in decreasing grain yield for R1F1M1 for both years. Increasing *finert* for R1F1M1 leads to a direct reduction of the decomposable carbon pool and therefore reduces nutrient release and increasing *soil_cn* slows the decomposition process itself. Reduced N leaching losses in 1995 explain the greater sensitivity of grain yield to *OC* content in 1995 compared to 1994. Grain yield of R1F1M1 was also sensitive to initial *NO3_ppm* content but only in 1994. This is ascribed to nitrate leaching from the heavy rainfalls of that year and thereby low residual nitrate content at the start of 1995.

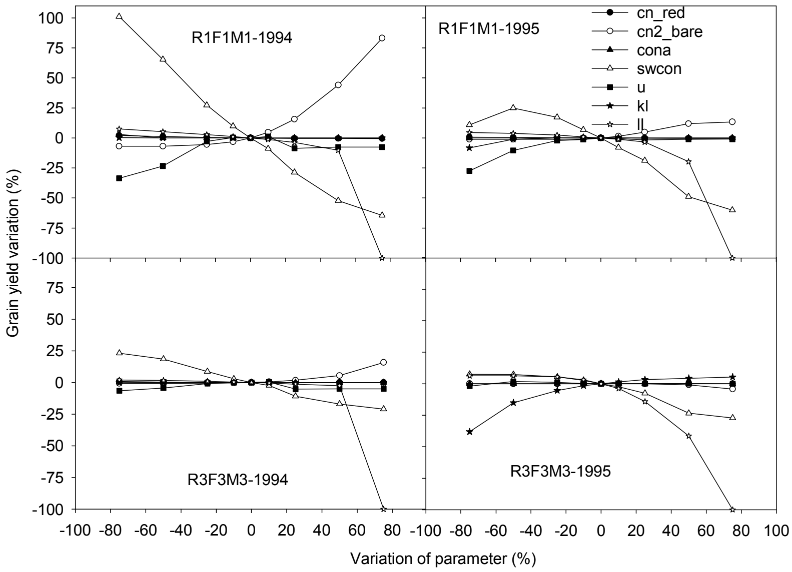


Figure 5.10. APSIM sensitivity analysis of millet grain yield to water balance related parameters in experiment III for the lowest (R1F1M1) and the highest (R3F3M3) amendment application rates in 1994 and 1995 at ICRISAT Sahelian center, Sadoré, Niger.

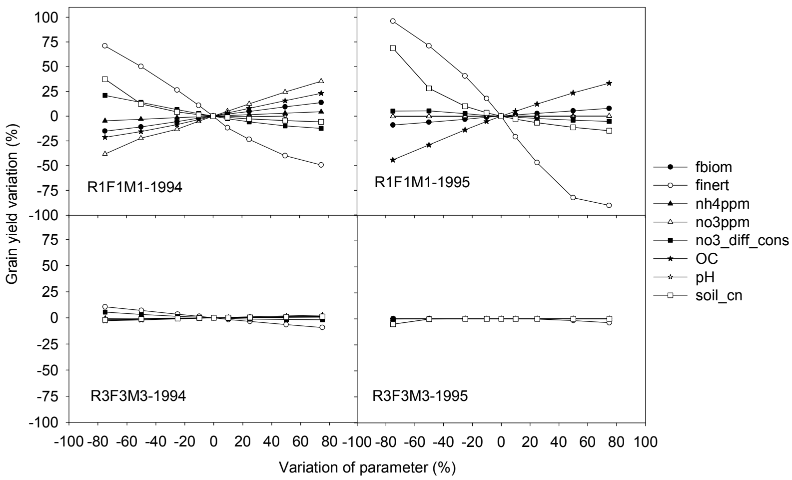


Figure 5.11. APSIM sensitivity analysis of millet grain yield to soil chemical related parameters in experiment III for the lowest (R1F1M1) and the highest (R3F3M3) amendment application rates in 1994 and 1995 at ICRISAT Sahelian center, Sadoré, Niger

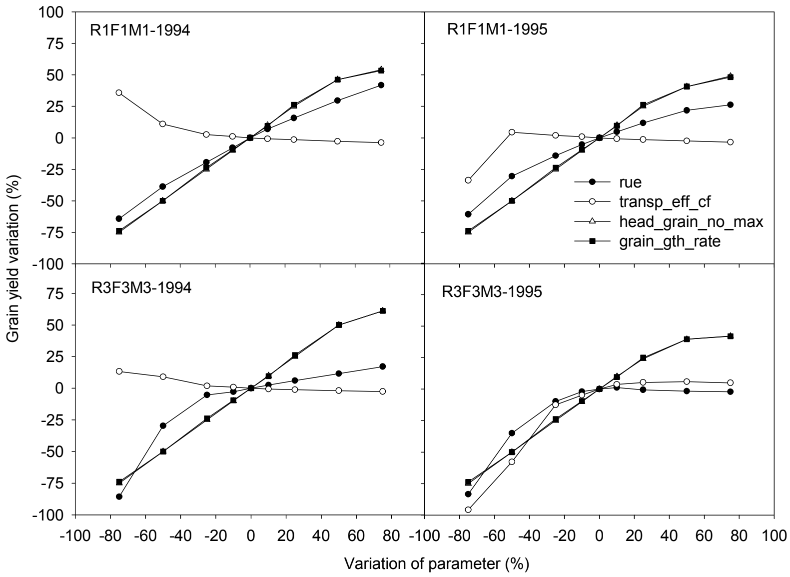


Figure 5.12. APSIM sensitivity analysis of millet grain yield to growth related parameters in experiment III for the lowest (R1F1M1) and the highest (R3F3M3) amendment application rates in 1994 and 1995 at ICRISAT Sahelian center, Sadoré, Niger.

Plant growth parameters Grain yield reacted strongly to changes in *grain_gth_rate*, *head_grain_no_max*, and *rue* with a virtually identical response in the case of *head_grain_no_max* and *grain_gth_rate* (Figure 5.12). Grain yield in the APSIM model is determined as the product of grain number and grain size. Grain number is dependent on the biomass at flowering and the potential or maximal value (*head_grain_no_max*) and grain size is determined by current biomass increment, stored biomass reserves, maximum grain growth rate and grain number. Grain yield was very sensitive to *transp_eff_cf* only in case of treatment R3F3M3 in 1995 as a result of the higher water stress in this treatment.

5.3.6 Long term term and factorial numerical simulation

Based on the long term and factorial numerical simulation, stover and grain yields have a similar response to N supplied as fertilizer and/or manure. Maximum and long term average grain yields increase parabolically in response to N input rates (Figure 5.14). Low N inputs (0 to 15 kg ha^{-1} N from manure and fertilizer) result in the lowest inter-annual variation in grain yield. At 15 kg ha^{-1} N, the long term average grain yield is 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. 15 kg ha^{-1} N guarantees at least 402 kg ha^{-1} every year while maximum grain yield reaches 742 kg ha^{-1}. 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}) but this goes together with a higher inter-annual yield variability and a slight decrease in minimum grain yield which is rather

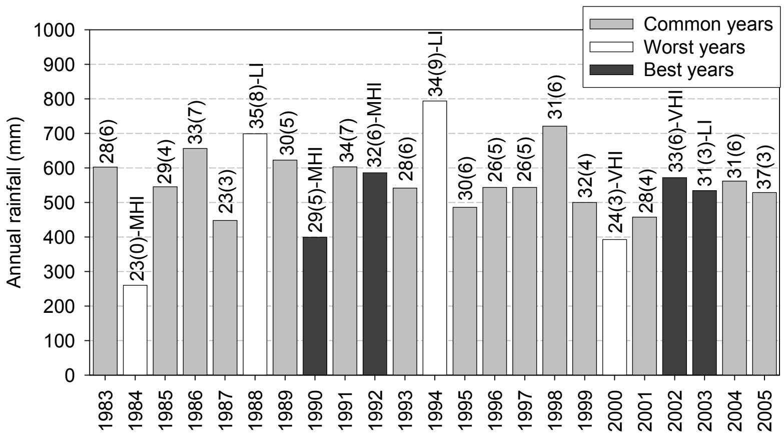


Figure 5.13. Annual rainfall, number of rainfall events (top labels) with number of heavy rains exceeding 30 mm, in brackets) at ICRISAT Sahelian center, Sadoré, Niger from 1983 to 2005. LI, MHI, VHI respectively denote low, medium to high and very high soil fertility intensification under which a year was identified as worst or best.

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 while the minimum yield decreases rapidly from 333 to 167 kg ha^{-1} and the inter-annual variability becomes very high.

Worst years (giving the lowest long term grain yield) were identified as 1984 and 2000 under medium to high and very high N input, respectively, and 1988 and 1994 for low N input (Figure 5.13). 1984 and 2000 were characterized by low harvest indices (grain / total biomass ratio between 0.08 and 0.15). Best years (giving the highest long term 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 (Figure 5.13).

5.4 Discussion

5.4.1 Performance of the model

In the context of model performance evaluation, it is essential to have a suitable control treatment, allowing to simulate soil water and N dynamics and subsequently the response to residue, manure and fertilizer applications. Traditionally, such a control treatment is viewed as being a zero-nutrient input treatment. In the experiment III dataset no such zero-input control 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 acidification and severe nutrient deficiency (e.g. Buerkert and Lamers, 1999; Bielders *et al.*, 2002) leading to millet grain yields < 100 kg ha^{-1} after just one year of cultivation, a rate of degradation which is never observed in traditional

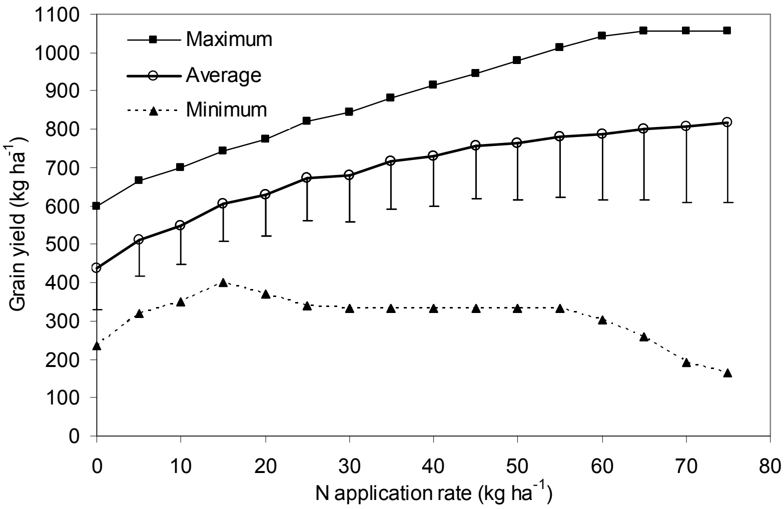


Figure 5.14. Statistical parameters of 23 year (1983 to 2005) simulated millet grain yield in response to N inputs from combined application of cattle manure and mineral fertilizer at ICRISAT Sahelian center, Sadoré, Niger. No residue was applied. Error bars denote standard deviation.

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 and representative of unfertilized farmer fields. In experiment III, 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. De Rouw and Rajot (2004a) estimated that passing herds leave behind about 100 kg ha^{-1} of dung. The lowest input treatment of experiment III may therefore be considered as an appropriate control treatment.

In addition to an excellent soil water calibration from experiment I, PAW validation results on experiment III were satisfactory (Figure 5.3). One may consider that the model reasonably predicted the temporal variations of PAW across 27 combinations of manure, residue and mineral fertilizer, because the average error in volumetric water content was only 0.8 to 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, no doubt, 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 and simulation results showed it 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 and even a little bit of water stress for the high fertilized treatment, measured grain yield was higher in 1995 than in 1994 (Figure 5.8b). This can be explained by the simulated N stress 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 (Figure 5.6b) but correctly reproduced the effect on grain yield. Water balance-based models cannot capture and explain these types of effects.

Model performance in predicting biomass throughout the growing season was fairly good and final biomass and grain yield predictions were realistic. Yet a close examination of the model performance showed that poor EF and RMSE values for biomass were observed mainly in case of treatments with high residue application R3 (2700 kg ha^{-1}), the worst being R3F3M3. Errors in model simulation 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. However, it must be noted that the CV of measured grain and stover yields ranged between 22 and 38%, which is high but 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 and the negative N immobilization effect (very low N content and high C/N ratio of millet stover). But the generally positive effect of residue on millet growth in the Sahel has been attributed to P mobility enhancement, decrease in exchangeable Al and soil protection against wind erosion (Buerkert *et al.*, 2000). These effects, and particularly the effect on P, are not taken into account by the APSIM model and hence the model cannot be used to simulate the response of millet to residue application in the Sahelian environment. Simulated biomass and grain yield performance was about 20 to 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).

5.4.2 Limitations of the model evaluation

Given the complexity of experiment III involving 27 combinations of millet residue, cattle manure and mineral fertilizer during two years with contrasted rainfall, we can consider that the APSIM-model performance was satisfactory in terms of millet response to N applied through manure and fertilizer at low levels of crop residue (Figure 5.9). However, two possible shortcomings of this model evaluation can be highlighted. First, nitrogen and water effects on yield were taken into account in the model but no measurements regarding the dynamics of nitrogen in soil were available. The availability of N measurements could have helped improve the model calibration/evaluation against this important factor. Secondly, 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 Sahelian region (Buerkert and Stern, 1995; Buerkert *et al.*, 2001). But at present the APSIM-millet module is not P sensitive and so adding P response in APSIM for millet crop could help improve the results. Nevertheless, some P was added in all treatments, mostly through fertilizer and / or manure, and this addition of P was approximately proportional to the amount of N added. The P/N ratio was 20% for manure and 29% for fertilizer. One may therefore expect that the added P was sufficient in most treatments so as not to limit millet yield, except for the treatments involving high levels of residue, low manure and no fertilizer. The latter treatments are anyway not well simulated since the main mechanisms of fertility enhancement through residues are not incorporated in the model. 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 although including P sensitivity would appear as an essential step towards improving model performance. At present, the model should be considered as validated with respect to N response under the condition that some P is added at the same time as N, which is anyway a prerequisite for N fertilization in the Nigerien Sahel (Buerkert *et al.*, 2001).

5.4.3 Long term factorial simulation and recommendations

Based on the two-year dataset of experiment III, grain yield can be expressed as a monotonously increasing function of N application rate, whether N is applied through manure or fertilizer (Figure 5.9). 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 minimum long term grain yield, were 1984 and 2000 for treatments where the N application rate exceeded 15 kg ha^{-1} N. 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, 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. For low N input, 1988 and 1994 lead to the lowest yields (Figure 5.13). 1988 and 1994 yields were 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; Figure 5.13). 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. Best years (giving the highest long term grain yield) were identified as 1990 and 1992 for medium to high N input and 2002 for very high N input and 2003 for low N input

(Figure 5.13). The reason for this was not clear. 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 these years 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. Based on the simulation results, inter-annual yield variability steadily increases at N application rates > 25 kg N ha^{-1} (Figure 5.14). This is consistent with the literature (Subbarao *et al.*, 1999). Equally important, one observes an optimum 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 0N treatment, without additional inter-annual variability. At rates > 15 kg N ha^{-1}, intensification becomes relatively riskier given the higher inter-annual variability and lower minimum guaranteed yield. This becomes very marked at rates > 55 kg ha^{-1} N. 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 interannual variability compared to no N input, it is not the most appropriate. The application of 15 kg N ha^{-1} seems more appropriate as it guarantees a higher minimum yield in extreme dry years and a lower interannual variability, thereby reducing the vulnerability of small-holder farmers. Based on yield, water use efficiency, partial factor productivity and nutrient balance criteria in a 2-year experiment, Akponikpè *et al.* (2008, Chapter 4) recommended (1) a low input combination of 300 kg residue and 2700 kg manure ha^{-1} without fertilizer (300R-2700M-0N0P) and (2) a combination of 900 kg residue ha^{-1}, 2700 kg manure ha^{-1} and 15 kg N + 4 kg P ha^{-1} (900R-2700M-15N4P). These two combinations supply 29.4 kg N ha^{-1} + 5.5 kg P ha^{-1} (300R-2700M-0N0P) and 49.1 kg N ha^{-1} + 9.9 kg P ha^{-1} (900R-2700M-15N4P), respectively, which are over the 15 kg N ha^{-1} recommendation of this long term numerical simulation. This situation shows all the benefit of the use of crop simulation models to complement experimental results. Firstly the experiment took place in 1994 (classified as a bad year due to high N leaching risk, Figure 5.13) and 1995 (an average year). The long term simulation showed that N application over 15 kg N ha^{-1} results in considerably reduced (minimum) millet yield in very dry years (such as 1984 and 2000, Figure 5.13). Secondly factorial experiments only consider discrete rates of application and the suitability of intermediate rates are difficult to access. Taking into account these additional information provided by the long-term simulation, one should prefer the 300R-2700M-0N0P combination to the second one 900R-2700M-15N4P keeping in mind that it remains very risky in very dry years. A good option would be to reduce the amount of manure in the combination to a rate around 1500 kg ha^{-1} (300R-1500M-0N0P). However one must verify that the nutrient balance of the latter combination remains positive for the main nutrient N, P and K.

5.5 Conclusions

Following the calibration with independent datasets, the APSIM model performance was fairly good in predicting 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 ($\leq$ 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 overall higher observed grain yield in 1995 compared to 1994, despite the better rainfall in 1994. This highlights the importance of considering water-nutrient interactions, even for environments for which water is (often wrongly) considered as the main constraint for crop production. 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 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 at 30 kg N ha^{-1}, the application of 15 kg N ha^{-1} appears more appropriate for smallholder, subsistence farmers than the usual 30 kg N ha^{-1} recommendation in as far as it guarantees higher minimum yield in extreme dry years and lower interannual variability, thereby reducing their vulnerability. Our results should be considered in conditions where P is added proportionally to N (P/N in the range of 20 to 30%). When N application originates from manure, no additional P will be requiered but mineral N application should be combined with proportionnal P.

Chapter 6

Effect of the spatial dispersion of farmer fields on the agro-climatic risk at household level in pearl millet-based systems in south-western Niger*

Abstract

The rainfall pattern in the Sahel is very erratic and unpredictable from year to year. We tested the hypothesis, often reported in research literature, that farmer disperse their field throughout the village territory to mitigate agro-climatic risk and by guaranteeing a stable yield. We found that the more dispersed farm fields of a household are, the less its yield is different from the average of other households in the village territory over years, in conditions of soil fertility gradient around village homestead or not. The field dispersion increases the inter-annual yield stability in a household (12-year simulation) but this relation depended on the rainfall data base used (6 years) and should be confirmed by further research on longer-term rainfall spatial data. We have demonstrated a method by which plot (or point)-level crop-soil dynamic models can be run over large land areas and the results can be aggregated to provide information at field, household and sub-regional (territory) levels. We have shown how GIS information, weather data, fertility management information and process-level plant-growth models can be integrated to evaluate farmers' or proposed strategies for agro-climatic risk management.

Keywords: rainfall, variability, risk, field dispersion, millet, GIS, soil fertility

6.1 Introduction

Sahelian rainfed cropping systems are characterized by a high climatic risk due to limited rainfall and high intra-seasonal drought risk, both factors being highly variable

*Adapted from: Akponikpè P.B.I., Minet J., Gérard B., Defourny P. Bielders C.L. Does spatial dispersion of farmer fields affect the agro-climatic risk at household level in pearl millet-based systems in south-western Niger ? To be submitted in space over short distances. Together with the low inherent soil fertility, this is the main biophysical factor limiting the development of Sahelian agriculture, on which the major part of the population depends. Pearl millet [*Pennisetum glaucum (L.) R.Br.*], the main staple crop, is grown during the short rainy season from May to September, during which the rainfall pattern and the date of onset are of primary importance for a good harvest (Sivakumar, 1992). For example in Niamey, the length of the growing season is positively correlated with the earliness of the onset of rains, the date of onset being much more variable from one year to another than the date of ending of the raining season (Sivakumar, 1990). Occurrence of dry spells, a consequence of irregular temporal rainfall distribution during the season, is also critical especially when they strike at crop growth stages such as emergence, or grain filling (Winkel *et al.*, 1997).

Temporal rainfall variability has been reported at different time scales (year, month, day and hour). The rainfall coefficient of variation (CV) for inter-annual fluctuation for different locations in SW-Niger varies between 17% and 32% (Sivakumar, 1989), for a mean long term annual rainfall ranging between 300 and 600 mm in the rainfed Sahelian zone (Le Barbé and Lebel, 1997). More essential to agriculture is the daily rainfall variability expressed as the amount of rain per rainy day and the interval between rainy days. At the ICRISAT Sahelian Centre (ISC), the average amount of rain per day increases from 9.7 mm to 14.4 mm during the course of the rainy season (May - August). However, the standard deviation (SD) at the same time increases from 7.6 mm to 11.1 mm. The mean interval between the rains decreases during the course of the rainy season from 6 to 2 days (Graef, 2000).

Spatially, rainfall can vary considerably even within a few kilometers distance depending on the time scale considered. The regional rainfall data for SW-Niger showed a higher variability in a latitudinal (N-S) than in a longitudinal (W-E) direction (Sivakumar *et al.*, 1993). This is associated with a systematic North-South long term mean annual rainfall gradient of approximately 1 mm rainfall km^{-1}. Annual differences of 200-300 mm may occur in any directions within a radius of only 100 km. A maximum annual rainfall gradient of 42 mm km^{-1} and 64 mm km^{-1} was found across the 500 ha ISC research station in 1995 and 1996, respectively (Graef, 2000). Differences in daily rainfall may exceed 20 mm over a distance of only 3.2 km distance (Graef, 2000), which may have a major impact on crop growth.

This spatio-temporal variability of rainfall induces an important space-time variability of millet growth and yield, which implies that crop yields are very unpredictable (Graef and Haigis, 2001). The spatial variability of millet yield has been reported at the regional, field and plant level. The micro- and meso-variability of yield was mainly attributed to soil physical and chemical characteristics (Voortman *et al.*, 2004), and to shrubs distribution (Brouwer *et al.*, 1993; Gérard and Buerkert, 1999). However, the field scale and regional scale yield variability have a strong connection with rainfall distribution, and for similar soils and fertility management practices, it is not rare to have drastically different yields between fields separated by a few kilometres only (Graef and Haigis, 2001). Graef and Haigis (2001) conducted socio-economic surveys at two villages and reported that smallholder farmers have adopted a range of management strategies to reduce agro-climatic risk and to ensure at least a minimum yield. In order to reduce the climatic risk, the dispersion of fields cultivated by a single household throughout the village territory has been reported as one mitigation strategy to stabilize yield over years. Other spatial factors, such as the distance from the field to the village homesteads, were also mentioned as playing a crucial role in the reduction of the climatic risk because of the water x fertility interaction. Under good rainfall conditions, high fertility fields are expected to lead to better yields than low fertility fields, whereas these same high fertility fields may suffer more severely from drought than low fertility fields under poor rainfall conditions (Dandois Dutordoir, 2006). According to Graef (2000), most farmers fields are dispersed within 1-5 km distance. Although regarded as a common wisdom, the real contribution of field dispersal to the mitigation of climatic risk has never been tested. It is particularly difficult to test under field conditions because of the multiplicity of spatially highly variable factors affecting yields: soil chemical fertility (see, e.g. Brouwer *et al.*, 1993; Voortman *et al.*, 2004), soil hydrodynamic properties and crusting (Hoogmoed and Stroosnijder, 1984; Valentin, 1991; D'Herbes and Valentin, 1997), rainfall distribution (Lebel *et al.*, 1997; Le Barbé and Lebel, 1997; Hunt, 2000), pests and diseases, and genetic variability of local millet cultivars.

Crop simulation models are appropriate tools for assessing the climate and fertility-related production variability associated with particular management strategies in agricultural systems (Thorburn *et al.*, 2001; Gijsman *et al.*, 2002; Jones *et al.*, 2003; Kpongor, 2007; Moeller *et al.*, 2007). Thornton *et al.* (1997) developed a prototype GIS-based, real-time yield forecasting system for Burkina Faso that uses CERES-Millet and satellite-derived precipitation estimates combined with historic weather data series. The integration in a GIS of spatially-distributed weather data and soil fertility information with crop simulation models appears as the most suitable means for evaluating the pertinence of farmers' climatic risk management strategies, and in particular for evaluating the extent to which field dispersion may help mitigate this risk.

The objective of this work is therefore to evaluate the impact of the spatial dispersion of farmer's fields on inter-annual millet yield stability at the household level by combining GIS land tenure information, soil fertility strata, spatial rainfall information and the APSIM crop growth simulation model.

6.2 Materials and methods

6.2.1 Study area

The study site covers an area of approximately 500 km^2 in the Fakara canton located 75 km to the east of the Niger state capital, Niamey (Figure 6.1). In this area, the study was centred on a 15 x 15 km zone around the village of Banizoumbou (13°58'N, 2°49'E) for which land tenure was combined with high resolution spatial rainfall data over a 6 year period and coarse resolution soil fertility data.

The climate of the Fakara is a typical inland semi-arid tropical climate. Being close to Niamey and approximately at the same latitude, the long term climatic characteristics can be considered similar to those of Niamey, with an average annual rainfall of 560 mm for the period 1905-1989 and of 495 mm only from 1968 to 1989 (Lebel *et al.*, 1997). Rains fall in summer when days are long, ambient temperatures are elevated, and potential evapo-transpiration is high. Rainfall distribution is strictly monomodal, centred in August, with rainy seasons lasting 4 to 5 months. The average date (and standard deviation) of onset of the rainy season is 12 June (18 days) and the average date of ending of rains is 27 September (12 days)(Sivakumar, 1988).

Soils differ across landscape but all tend to have low organic carbon content ($<$ 0.3%) and a weakly developed structure (West *et al.*, 1984). Cropped soils are mainly sandy ($>$85% sand) and belong to the arenic Gleysols, gleyic Arenosol, leptic Lixisol, arenic Lixisols, and arenic Cambisol types (Hiernaux and Ayantunde, 2004). Topsoils are acidic and poor in total nitrogen and available phosphorus with a generally very low cation exchange capacity (1-2 cmol kg^{-1}).

The cropping system is largely subsistence-oriented, based on millet sometimes associated with a range of secondary crops, either dual-purpose legumes (cowpea, Bambara nut, groundnut) or cash crops (sesame, sorrel). Because of the sandy texture, zero tillage is practiced and the bottleneck of cropping is often the labour required for weeding. Average land cropped per household is about 2.3 ha and 13.2 ha per adult equivalent, this reflecting the low yields and low population density (Hiernaux and Ayantunde, 2004).

6.2.2 GIS household-level land tenure data

Household-level land tenure (household field ownership) refers to the set of geo-referenced, individual fields cropped by a given household. The land tenure map of the Banizoumbou land territory was established by a research team of the International Livestock Research Institute (ILRI) in 1996 by combining aerial and satellite imagery and an exhaustive socio-economic survey of the households in the area between 1994 and 1996 (Figure 6.1) (Hiernaux and Ayantunde, 2004). All fields cultivated by 107 households are included in this map. We considered all fields in the land tenure as cropped every year although a few of them may not be in reality (fallow). The vector information of the observed land tenure of Banizoumbou (15 x 15 km) was converted into raster with a pixel resolution of 100 m. The pixel size was imposed by the smallest field size.

6.2.3 Spatial rainfall estimation

Data from two networks were used. The first network, monitored by the Institut de Recherche pour le Développement (IRD-Niamey), was a finely distributed one with 66 rainfall gauges regularly spaced on a 170 x 90 m grid covering an area of 76.5 ha and monitored during the 2006 rainy season. The second network monitored by ICRISAT comprised between 50 and 70 rainfall gauges (depending on the year) distributed randomly across the whole canton of the Fakara. It has been monitored from 2000 to 2005 for daily rainfall during the rainy seasons (Figure 6.1). Rainfall gauges were spaced between 1 and 5 km from each other. The 15 x 15 km Banizoumbou village territory was covered by 20 rainfall gauges.

Data from the two rain gauge networks were first verified for consistency and abnormal values (Van Vyve, 2006; Minet, 2007). Twenty three rainfall events from the IRD network were selected and used to derive a variogram model of the daily rainfall

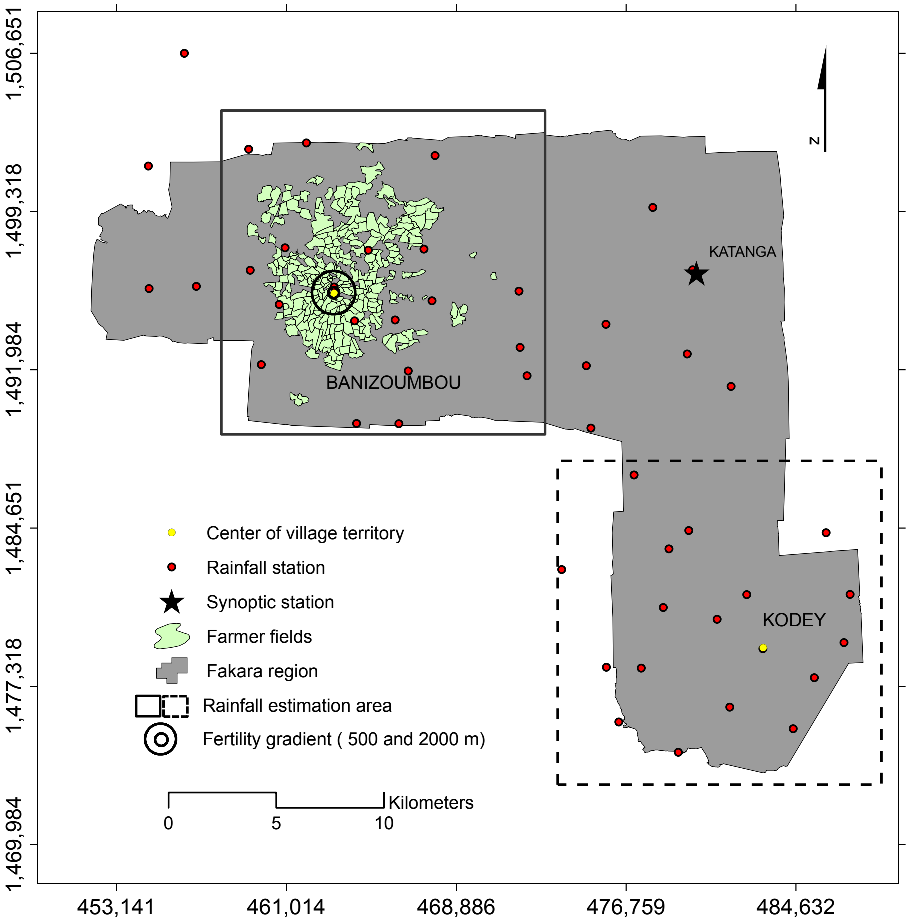


Figure 6.1. The Fakara study site, Banizoumbou land tenure and ICRISAT climatic network. Coordinates are in WGS 1984 UTM 31N.

(Minet, 2007). A nested gaussian-spherical model was fitted to the variogram having the following characteristics: 12 mm^2 sill, a range of 4 km with no nugget effect. The BMELIB2.0b Matlab® geostatistical library was used to derive the variogram and the fitted model parameters (Christakos *et al.*, 2002). The derived variogram model from the first network was used with the measured data of the ICRISAT network to estimate daily rainfall for each pixel (2500 of 300 x 300 m) of the 15 x 15 km Banizoumbou area over a 6-year period (2000 to 2005) using the Cholesky conditional interpolation function $simucholcond.m$ of BMELIB2.0b. Estimated daily rainfall less than zero were considered as nil. In order to increase the range of rainfall conditions beyond the six years of observed data at Banizoumbou, the spatial rainfall data from the nearby village of Kodey (13°22'N, 2°51'E, 26 km from Banizoumbou) also covering a 15 x 15 km area, was superimposed on the Banizoumbou land map. This area was covered by a network of 17 rainfall gauges and observed values were interpolated using the same procedure as for Banizoumbou. Rainfall data from Banizoumbou and Kodey are considered spatially independent, given that the range of the daily rainfall variogram is of the order of a few kilometres whereas the villages are separated by 26 km from each other.

6.2.4 Millet biomass and grain yield simulations

The Agricultural Production Systems Simulator APSIM was used to simulate millet grain and total aboveground biomass yield. APSIM is a modular modelling framework that has been developed by the Agricultural Production Systems Research Unit in Australia (Keating *et al.*, 2003). Five modules - a specific millet crop module (APSIM-millet 3.6), a soil water module (Soilwat2), the soil nitrogen (Soiln2), the residue (Residu2) and the manure (manure) module - were linked within APSIM to simulate the cases described in this paper. Input data required by the APSIM model are related to the soil chemical and physical properties, crop genetic characteristics, crop management (sowing, soil amendments, etc.) and climate data.

The cultivar used in the simulations was the most commonly used landrace (Hainikirey) in the region. APSIM was parameterized for this cultivar based on independent data collected at ICRISAT Sadoré in 2005 (see chapter 3). Sowing was allowed when a total rainfall over 15 mm occurred over three consecutive days between May 1st and June 30 each year. 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. Resowing of millet in case of crop failure is frequently practiced by farmers in the area. 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 15000 plants ha^{-1}, which is comparable to the densities found in farmer fields in the area (Payne, 1997, 2000).

Initial soil chemical and physical parameterization was based on literature and calibration from previous crop model validation works with CERES (Fechter *et al.*, 1991; Fechter, 1993) and APSIM (Akponikpè *et al.*, 2006, 2007). These soil properties were considered as spatially homogeneous because related APSIM model testing showed no significant difference in millet yield response to the chemical (Ska, 2005) and the physical (Weynants, 2005) spatial variability observed in the Fakara region. No spatial soil micro-variability was considered, and initial soil chemical parameters were reset at each simulation year. To reproduce the soil fertility gradient around villages we used two scenarios: (1) no fertility gradient (-FG); in this case, 300 kg ha^{-1} millet stover was applied for every pixel, which is representative of the amount usually found in most farmer fields before planting (Baidu-Forson, 1995), (2) fertility gradient (+FG) from the center of the village : 300 kg ha^{-1} crop residue + 3000, 300 or 0 kg ha^{-1} manure applied when the simulated pixel is located 0-500 m, 500-2000 m or over 2000 m, respectively, from the village centre. Levels of manure application were chosen to reproduce the natural soil fertility gradient around villages in the area. Millet response to combined application of low rates of crop residue and manure using the APSIM model was previously satisfactorily tested regarding water and N interactions (Akponikpè *et al.*, 2007, Chapter 5).

Climate data (minimum and maximum temperatures, solar radiation) were recorded daily over the 6 years by means of a Campbell CR10 automatic weather station located at the Katanga village, approximately 10 km away from Banizoumbou (Figure 6.1). These climatic characteristics were considered spatially homogeneous. The spatially homogeneous initial soil fertility, crop genetic properties and temperature and solar radiation data were combined with the spatially variable rainfall data (2 x 6 years) and fertility management practices in the APSIM model to simulate millet biomass and grain yield at each of the 2500, 300 x 300 m size pixels. A computer code was developed with the Matlab® language (Mathworks, 2007) that manages and combines the GIS climate, soil fertility management inputs and calls the APSIM model to run the simulation at each pixel (2500) and year (12). The simulated millet yield of all the 9 100 x 100 m^2 pixels falling within a 300 x 300 m pixel was considered equal. The biomass and grain yield of a given field was computed as the average value of all 100 x 100 m pixels falling within it. An overview of the simulation approach and its integration with spatial data in a GIS is presented in Figure 6.2.

6.2.5 Household fields dispersion and agro-climatic risk indicators

Household field dispersion index The Convex Hull (CH) (Bishop, 2007) was used as an index of farmer fields' dispersion and was computed for each household in ArcGIS 9.1 . It is defined as the area of the smallest bounding polygon which surrounds all the fields owned by a given household (Figure 6.3). It is a function of the separation of the fields. For the case of a household with only one field, the CH is equal to the field area.

Agro-climatic risk indicators Two agronomic risk indices were computed:

1. the inter-annual, standard deviation of millet grain (SD_GY_HD) or biomass (SD_BY_HD) yield, calculated for each household (HD) separately. Let Y_{ijk} be the grain yield (kg ha^{-1}) of field i in household j during year k, s_i the area (ha) of field i and m the number of fields cultivated by household j, then the

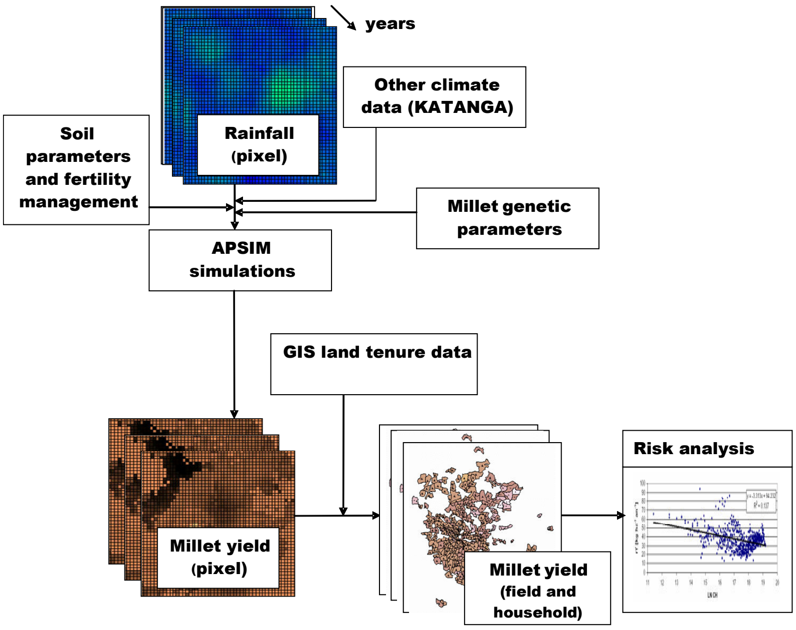


Figure 6.2. Diagram of the method using APSIM model to evaluate the relation between household fields' spatial dispersion and agro-climatic risks

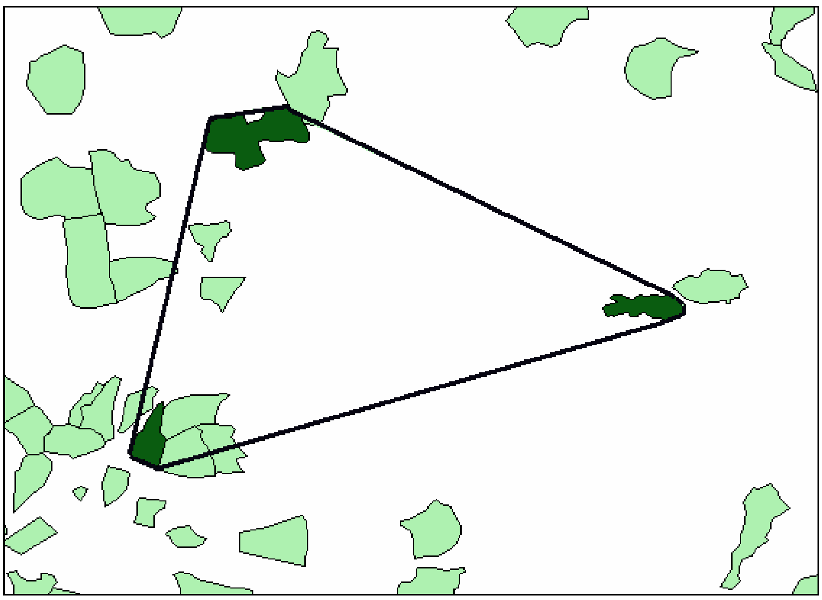


Figure 6.3. Convex hull (CH) delimitation for a household owning three farm fields

weighted average grain yield in household j during year k is given by:

$$Y_{jk} = \frac{\sum_{i=1}^{m} s_i Y_{ijk}}{S_j} \tag{6.1}$$

where

$$S_j = \sum_{i=1}^{m} s_i \tag{6.2}$$

is the total area cultivated by household j. The average grain yield of household j over n cropping years is given by :

$$Y_j = \frac{1}{n} \sum_{k=1}^{n} Y_{jk} \tag{6.3}$$

The SD_GY_HD index for household j is then given by :

$$SD\_GY\_HD_j = \sqrt{\frac{1}{n-1} \sum_{k=1}^{n} (Y_{jk} - Y_j)^2} \tag{6.4}$$

SD_BY_HD is calculated in a similar way, replacing millet grain yield by total aboveground millet biomass (kg ha^{-1}). The lower the value of SD_GY_HD or SD_BY_HD, the more stable grain and biomass yield are over years for a given household.

2. the inter-annual, standard deviation over years of grain (SD_GY_TR) or biomass (SD_BY_TR) yield relative to the average yield across the village territory (TR). The average yield across the village territory in year k is given by :

$$Y_k = \frac{\sum_{j=1}^{h} S_j Y_{jk}}{\sum_{j=1}^{h} S_j} \tag{6.5}$$

where h is the total number of households. SD_GY_Tr for household j is then given by :

$$SD\_GY\_TR_j = \sqrt{\frac{1}{n-1} \sum_{k=1}^{n} (Y_{jk} - Y_k)^2} \tag{6.6}$$

SD_BY_TR is calculated in a similar way, replacing millet grain yield by total aboveground millet biomass. The lower the value of SD_GY_TR or SD_BY_TR, the closer the grain and biomass yield of a given household are to the average village scale yield each year.

Results were analyzed in terms of the cumulative probability density distribution of the two indices with or without consideration of a fertility gradient. Simple regression analysis between CH and the risk indices was also performed.

6.3 Results

6.3.1 Spatial rainfall, sowing events and millet yields

Rainfall distribution (yearly) The spatially-averaged annual rainfall at village territory scale ranged from 395 to 505 mm across the 6 years of observations over the 2 sites (Table 6.1). However, the spatial variability of rainfall for a given year and site was much larger than the temporal variability of the spatially-averaged annual rainfall. Indeed, the difference between the wettest and driest pixels (300 x 300 m) ranges between 197-262 mm for Banizoumbou (Figure 6.4) and 187-265 for Kodey (not shown) depending on the year, which is consistent with observations. In addition, despite the limited range in the spatially-averaged yearly rainfall values, the spatial rainfall pattern varied greatly across years (Figure 6.4). At a daily scale, the spatial heterogeneity was even larger.

The same conclusions apply when considering the average rainfall at household level in the land tenure map (Figure 6.1). Although the CV (between rainfall of all households in the territory in a given year) is rather low (4 to 10%; Table 6.1), important variability of annual cumulative rainfall between household was observed with a difference between wettest and driest houselhold ranging between 100-158 mm (Banizoumbou) and 109-212 mm (Kodey) depending on the year.

Sowing events The date of the first sowing varied very much between pixels (not shown). The earliest sowing took place on May 05 in 2005 and the latest on July 18 in 2000 and 2002 for the Banizoumbou rainfall dataset. The maximum range between the earliest and latest sowing date (at pixel level) varied from 21 (2003) to 55 days (in 2002) (not shown). A re-sowing was necessary in 2000 and 2001 in some parts of the village territory (Figure 6.5).

Biomass and grain yields At the pixel scale, biomass and grain yields were spatially coherent, i.e., the yield of a pixel was closely related to those of its neighbours (Figures 6.6 and 6.7). The spatial structure of biomass and grain yields were similar, the average coefficient of correlation between the two variables was indeed higher than 0.9. An opposite trend was perceptible when comparing the spatial structure of sowing dates and yields, i.e., late sowing tended to induce lower yields, and the yield pattern was sometimes particularly well explained by the sowing date pattern. The relation between annual rainfall and biomass or grain yields was low to moderate. The correlation coefficient between grain yield and annual rainfall varies between -0.20 and 0.30 depending on the year.

Without fertility gradient, the average, household-level yields varied between 334 and 542 kg ha^{-1} for grain yield and between 1609 and 3031 kg ha^{-1} for biomass, with slightly higher values in the presence of a fertility gradient around the village (Table 6.1). The variability of biomass and grain yields across households was higher than rainfall with a CV ranging from 4 to 26% depending on site and year in the absence of fertility gradient around the village, with a maximum range from 60 to 466 kg ha^{-1} for grain yield and 647 to 3200 kg ha^{-1} for biomass yield. Taking into account the fertility gradient around the main village tended to increase the maximum ranges and

Table 6.1. Average, CV% and skewness of rainfall, millet biomass and grain yield per household in land tenure of Banizoumbou and Kodey, Niger. -FG and +FG are scenario without and with fertility gradient around the village.

		Rainfall(mm)	Biomass (kg ha^{-1})		Grain (kg ha^{-1})	
			-FG	+FG	-FG	+FG
Baniz.[a]	2000	431 [7(1.2)]	1777 [25(-0.8)]	1886 [28(0.0)]	338 [20(-0.9)]	355 [22(-0.3)]
	2001	395 [7(0.5)]	2594 [11(0.0)]	2710 [15(1.1)]	445 [10(0)]	461 [12(0.7)]
	2002	398 [8(0.5)]	3031 [6(-1.1)]	3082 [7(-1.1)]	542 [5(-0.4)]	553 [6(0.6)]
	2003	505 [4(0.2)]	1609 [18(0.3)]	1763 [19(1.9)]	298 [13(0.1)]	328 [15(2.5)]
	2004	395 [7(-0.6)]	2183 [19(-0.3)]	2273 [22(0.4)]	407 [18(-0.1)]	421 [20(0.4)]
	2005	445 [5(0.4)]	2665 [14(-0.4)]	2781 [17(0.2)]	471 [13(-0.4)]	490 [14(-0.1)]
Kodey[b]	2000	469 [7(0.9)]	1816 [26(-0.1)]	1940 [29(0.7)]	334 [21(-0.2)]	352 [22(0.3)]
	2001	395 [7(1.2)]	2499 [13(0.0)]	2619 [17(1.2)]	439 [10(-0.1)]	455 [12(0.5)]
	2002	500 [4(0.2)]	2963 [8(-0.1)]	3063 [11(1.2)]	521 [4(-0.8)]	534 [6(1.6)]
	2003	396 [9(-0.5)]	2378 [4(-0.2)]	2509 [11(3.4)]	419 [4(0.2)]	441 [10(2.5)]
	2004	474 [6(0.3)]	2917 [5(-1.5)]	3005 [8(1.2)]	529 [4(-1.3)]	543 [6(1.2)]
	2005	455 [10(0.5)]	2755 [12(-0.8)]	2862 [15(-1.2)]	478 [11(-0.8)]	494 [13(-1.4)]

[a] real data and simulations for Banizoumbou territory

[b] rainfall data from another but close territory (Kodey) used to extend the number of simulation years from 6 to 12 with the assumption that the rainfall pattern at a site in a given year may happen at another site and year.

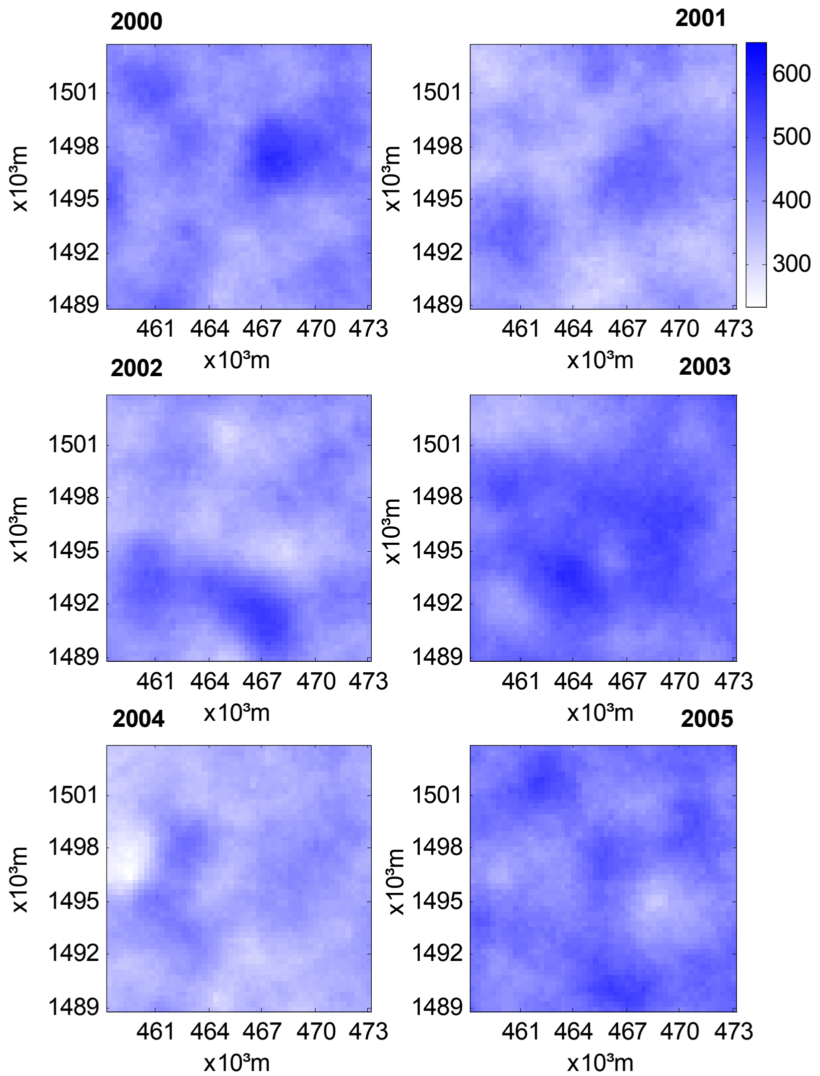


Figure 6.4. Spatially estimated rainfall [mm] at pixel level (300 x 300 m) from 2000 to 2005 at Banizoumbou, Niger; coordinates are in WGS 1984 UTM 31N.

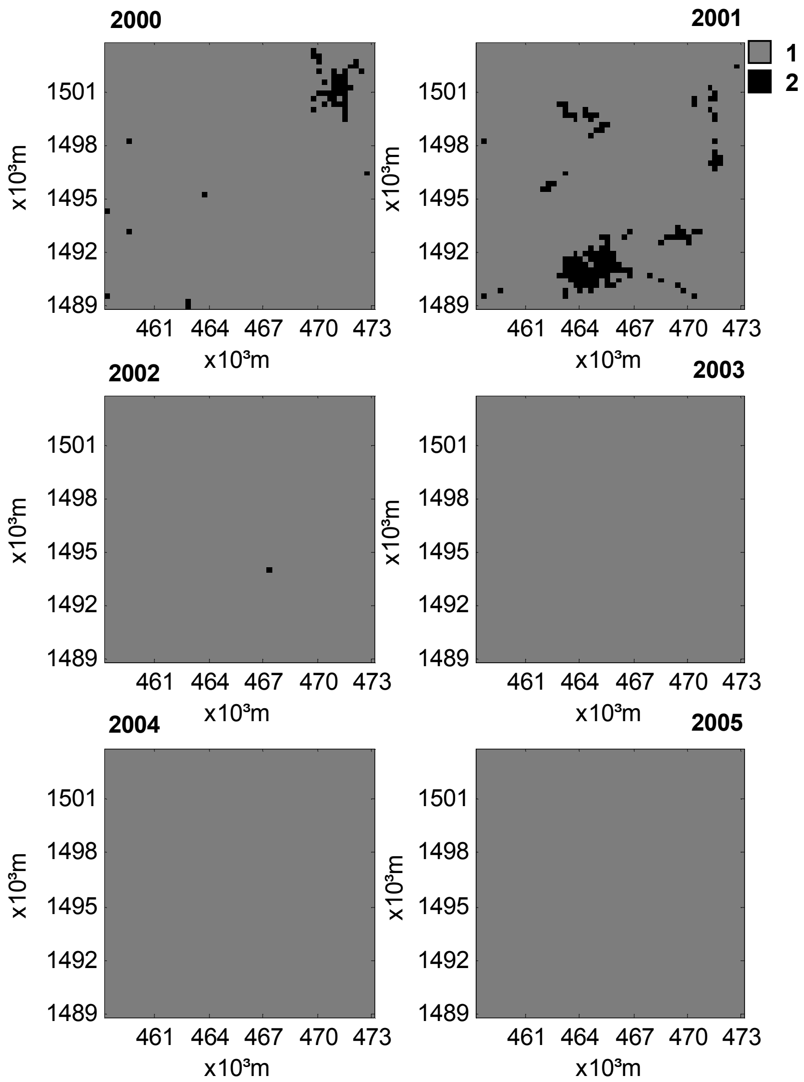


Figure 6.5. Spatially simulated number of sowing events [-] at pixel level (300 x 300 m) from 2000 to 2005 at Banizoumbou, Niger; coordinates are in WGS 1984 UTM 31N.

CV (Tables 6.1, Figures 6.7).

6.3.2 Agro-climatic risk indicators

The variability of biomass and grain yield was higher between years within the same household [444 kg ha^{-1} (10%) for SD_BY_HD and 67 kg ha^{-1} (11%) for SD_GY_HD] than between a household and the average village-wide yield [139 kg ha^{-1} (19%) for SD_BY_TR and 22 kg ha^{-1} (16%) for SD_GY_TR] (Figure 6.8). SD_BY_HD and SD_GY_HD tended to decrease when taking into account the fertility gradient around the village, whereas those of SD_BY_TR and SD_GY_TR tended to slightly increase (Figure 6.8).

6.3.3 Relation between risk indices and spatial dispersion of household fields

The CH values ranged between 0.03 and 25.37 km^2 depending on the household. In general, the indices decreased exponentially with increasing values of the CH, as illustrated in Figure 6.9a,c, indicating that both the inter-annual yield variability at household level and the difference between household yield and average village-level yield tended to decrease with increasing spatial dispersion of fields.

Based on linear regression analysis after logarithmic transformation of the CH, the linear regressions between Ln(CH) and SD_BY_TR or SD_GY_TR were all highly significant with negative slopes for the two fertility gradient scenarios around the village (Table 6.2). Taking into account the fertility gradient tended to increase the slope (in absolute term) i.e. increased field dispersion reduced SD_GY_TR or SD_BY_TR more strongly when a fertility gradient is present compared to when it is not.

On the other hand the relations for SD_BY_HD and SD_GY_HD were weak (though often with negative slope) and were dependent on the rainfall dataset (Banizoumbou or Kodey) and fertility gradient (Table 6.2). These relations were significant (except for SD_GY_HD with +FG) for Banizoumbou (6 years) and the grouped site rainfall data (12 year) but not for Kodey (6 year).

6.4 Discussion

The objective of this paper is to evaluate the relation between the dispersion of household farm fields the agro-climatic risk. For this purpose, we geostatistically estimated daily rainfall at pixel level to simulate over a 12 year period, with the APSIM crop-model, millet biomass and grain yields that were combined with a land tenure map in a GIS. No spatial micro-variability factor was taken into account apart from the rainfall spatial variability; nevertheless a soil fertility gradient around the village was reproduced by digressive manure application rates.

The maximum range of annual rainfall was high at pixel level (187-265 mm over 15 km or 12-18 mm km^{-1} and 10% CV) whereas at household level, in the real land tenure, it was 100-212 mm over 15 km or 7 to 14 mm km^{-1} and 4 to 10% of CV (Ta-

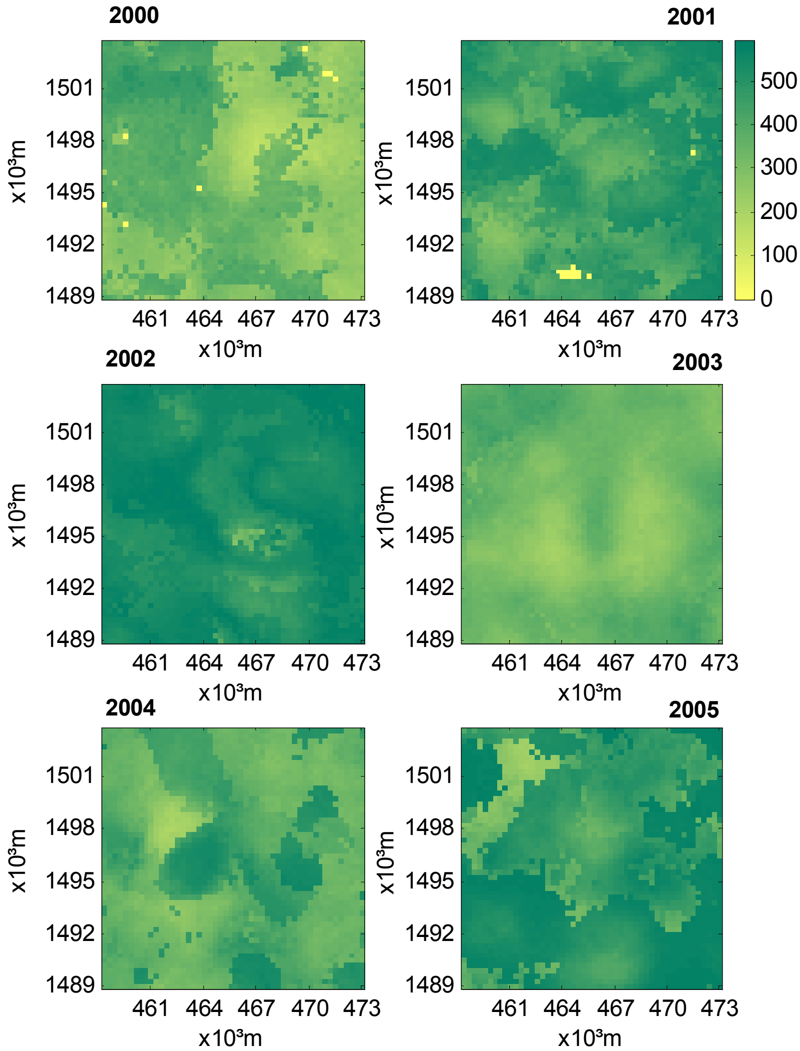


Figure 6.6. Spatially simulated grain yield [kg ha^{-1}] without fertility gradient at pixel level (300 x 300 m) from 2000 to 2005 at Banizoumbou, Niger; coordinates are in WGS 1984 UTM 31N.

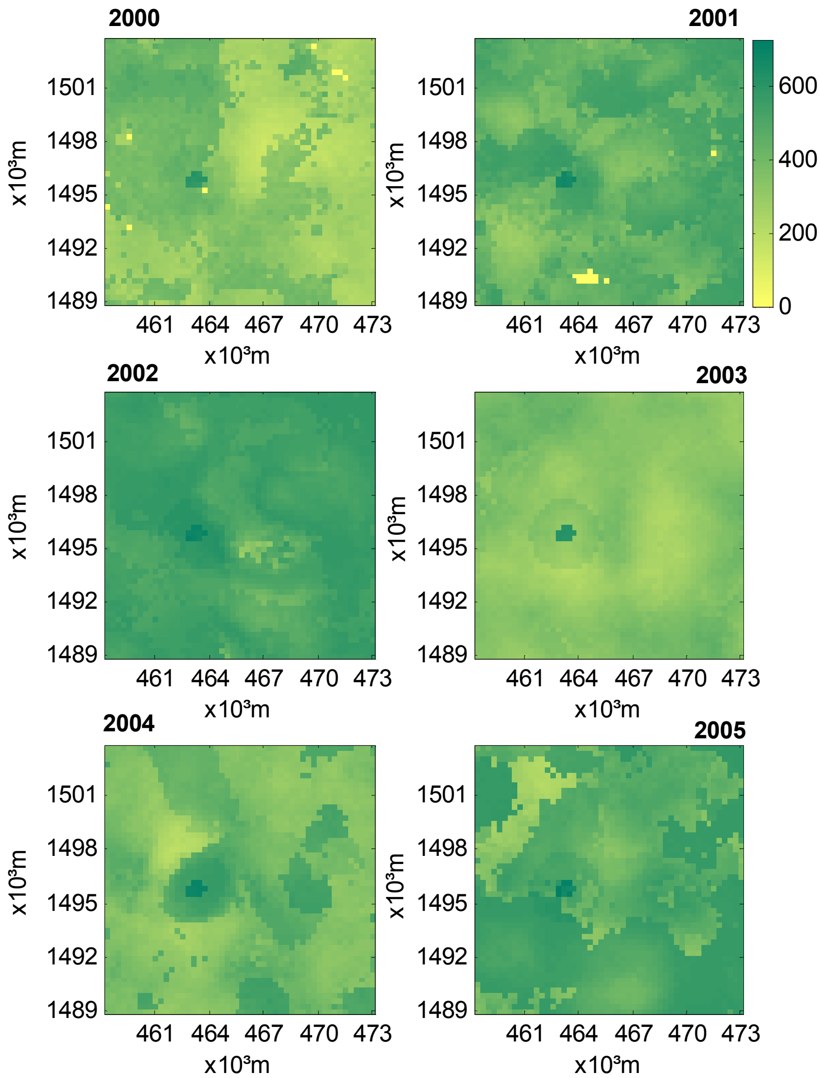


Figure 6.7. Spatially simulated grain yield [kg ha^{-1}] with fertility gradient at pixel level (300 x 300 m) from 2000 to 2005 at Banizoumbou, Niger; coordinates are in WGS 1984 UTM 31N.

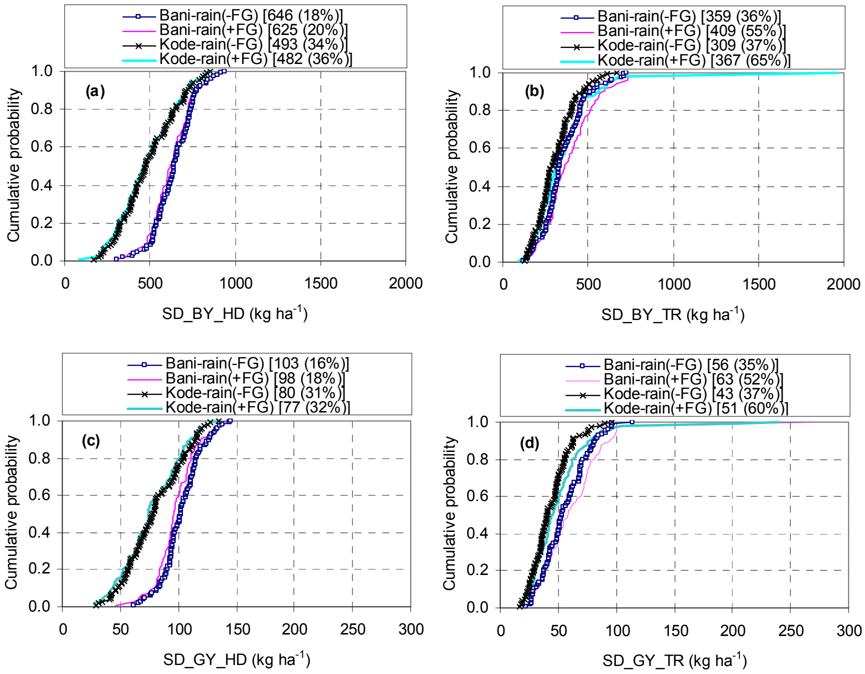


Figure 6.8. Cumulative probability of agro-climatic household-level risk indices for biomass [SD_BY_HD (a) and SD_BY_TR (b)] or grain yield [SD_GY_HD (c) and SD_GY_TR (d)] accounting for the fertility gradient (+FG) around the village homesteads or not (-FG). Bani-rain and Kode-rain denotes respectively simulations (2000 to 2005) with rainfall data from Banizoumbou or Kodey, respectively.

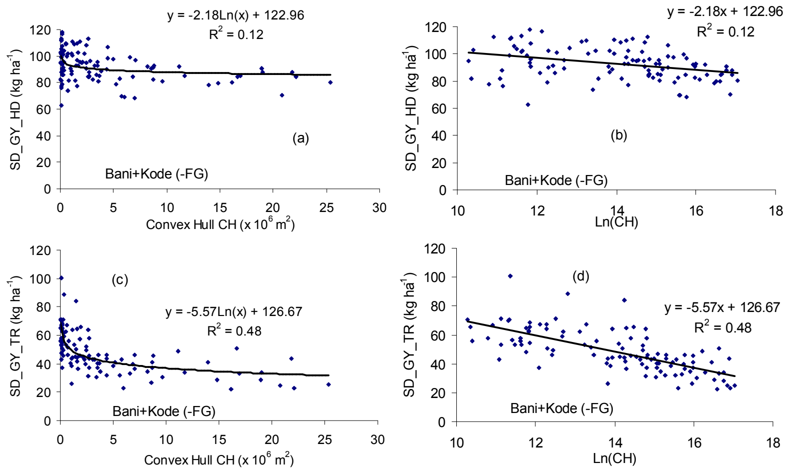


Figure 6.9. Example of the relation between agro-climatic risks SD_GY_HD (a, b) and SD_GY_TR (c, d) and household fields' spatial dispersion index or convex hull CH in the real land tenure for Banizoumbou and Kodey rain combined (12 years, without fertility gradient (-FG)).

Table 6.2. Regression analysis between risk indexes (SD_BY_HD, SD_GY_HD, SD_BY_TR and SD_GY_TR) and Ln(CH) in the land tenure of Banizoumbou, Niger. -FG and +FG are scenario without and with fertility gradient around the village.

		SD_BY_HD		SD_GY_HD	
		-FG	+FG	-FG	+FG
Bani-rain	Slope	-17.5**	-12.8*	-3.2***	-1.7 ns
(6 years)	intercept	891.5***	803.8***	148.1***	122.3 ns
	R^2	0.07**	0.04*	0.12***	0.03 ns
Kode-rain	Slope	-5.8 ns	-2.9 ns	-0.5 ns	0.1 ns
(6 years)	intercept	574.1 ns	522.9 ns	87.1 ns	75.3 ns
	R^2	0.00 ns	0.00 ns	0.00 ns	0.00 ns
All	Slope	-13.4***	-10.5*	-2.2***	-1.1 ns
(12 years)	intercept	767.2***	711.7***	123.0***	103.6 ns
	R^2	0.10***	0.05*	0.12***	0.02 ns
		SD_BY_TR		SD_GY_TR	
		-FG	+FG	-FG	+FG
Bani-rain	Slope	-43.4***	-65.7***	-6.9***	-10.3***
(6 years)	intercept	967.3***	1328.8***	153.1***	207.1***
	R^2	0.38***	0.29***	0.43***	0.32***
Kode-rain	Slope	-33.4***	-57.0***	-4.4***	-7.4***
(6 years)	intercept	777.7***	1165.7***	104.6***	154.0***
	R^2	0.29***	0.19***	0.24***	0.20***
All	Slope	-37.6***	-59.5***	-5.6***	-8.6***
(12 years)	intercept	852.6***	1210.1***	126.7***	175.5***
	R^2	0.48***	0.27***	0.48***	0.30***

ns = not significant; *, **, *** probability significant at 0.05, 0.01, 0.001 respectively.

ble 6.1). There is a smoothing effect of spatial variability when aggregating (average) from pixel to farm field and household levels. Even higher annual rainfall gradients (42 mm km^{-1} and 64 mm km^{-1}) were reported by Graef (2000) over the ISC (500 ha) respectively in 1995 and 1996. The spatial variability of cumulative annual rainfall was lower than the one at daily level due to a comparable smoothing effect when aggregating (sum) from daily to annual scale. The relation between the annual rainfall and the yields (biomass or grain) at pixel level was low and depended on years and pixel location (rainfall condition). This is a well-known fact in the Sahelian environment. Popov (1984) found from the analysis of 32 years of climatic data and crop yields that between 400 and 1200 mm of rainfall, yield could not be adequately explained by changes in annual rainfall. The same low correlation between annual rainfall and yield was also reported by De Rouw and Rajot (2004b). Rainfall distribution, sowing condition and soil fertility management are to be integrated together to adequately predict crop yield in the Sahel (Akponikpè *et al.*, 2007). Late sowings (21 to 55 days difference with first sowing on the territory) often induced lower yields probably due to millet water stress toward the end of the cropping season (Do *et al.*, 1996). Whatever the date of onset of rainall in a given year, rainfall ends approximately at the same date. At Niamey (Niger) for instance, standard deviation (SD) for the average date of ending of rains (27 September) is only 12 days (Sivakumar, 1988), as opposed to 18 days for the date of onset (12 June).

At the pixel level simulated grain and biomass yield were comparable to published values in the area with and without various soil amendments (Bationo and Mokwunye, 1991a; Bielders and Michels, 2002; De Rouw and Rajot, 2004a,b) and were spatially coherent (or correlated). The spatial variability of annual rainfall induced a higher spatial variability of millet production. At the household level (in the real land tenure), the variations of biomass and grain yields were high with a CV from 4 to 28% in situation of no fertility gradient around the village, with maximum range of 60 to 466 kg ha^{-1} and 647 to 3200 kg ha^{-1}, respectively, for the grains and the biomass. This could be ascribed to the fact that yield is more dependent on daily rainfall distribution than on cumulative annual amount (moving from daily to annual scale smoothes in a significant way the rainfall variability) (Sivakumar, 1992; Winkel *et al.*, 1997).

Taking into account the fertility gradient around the village tended to increase, in a significant way, the maximum ranges and CV. Fertility gradient adds to be an additional source of yield variability. The variability of biomass and grain yield was higher between years within the same household (SD_BY_HD and SD_GY_HD) than between a household and other ones in the village territory (on average) (SD_BY_TR and SD_GY_TR) (Figure 6.8 and 6.6). This is a consequence of the unpredictable and erratic rainfall condition from year to year in the area (Sivakumar, 1988, 1992; Sivakumar *et al.*, 1993). In a given year the rainfall condition experienced by a household remains correlated to its neighbour's despite the existing spatial rainfall variability.

The linear regressions between Ln(CH) and SD_BY_TR or SD_GY_TR were all highly significant with a negative low to high slopes when taking into account or not the fertility gradient around the village. The more dispersed farm field are in a household, the less its yield is different from the yields of the other households in the territory over years. This shows that dispersed fields are better than a single field to minimize yield differences across households in a given territory and year.

The relations between SD_BY_HD and SD_GY_HD and field dispersion were weak (though often with negative slope and often significant) and were dependent on the rainfall dataset (site) and fertility practice (Table 6.2). This was rather unexpected, as field dispersion is generally seen as a means to dampen inter-annual yield variability. Although showing the same tendency, statistical significance was not observed for Kodey. For SD_GY_TR (and SD_BY_TR), the probability distribution functions are quite similar for both sites rainfall, and the slopes of the regressions SD_GY_TR (or SD_BY_TR) vs Ln(CH) are also close (Figure 6.8, Table 6.2). But for SD_GY_HD (or SD_BY_HD), the probability curves are very different, with a much wider distribution of values for Kodey rainfall than for Banizoumbou.

Because the relation was more consistent and significant with longer (12 years) rainfall spatial data, this relation should be confirmed by further research on longer-term rainfall spatial data.

6.5 Conclusion

We have demonstrated a method by which plot (or point)-level crop-soil dynamic models can be run over large land areas and the results can be aggregated to provide information at field, household and sub-regional (territory) levels. We have shown how GIS information, weather data, fertility management information and process-level plant-growth models can be integrated to evaluate farmers' or proposed strategies for agro-climatic risk management. The main outcomes of this work are the following: (1) the spatial variability of cumulative annual rainfall was lower than the one of the daily rainfall at pixel and household levels; (2) the spatial variability of annual rainfall induced a higher space variability of millet production both at pixel and household levels; (3) the fertility gradient around village homestead increases the millet yield variability between households in a given territory (real land tenure); (4) the more dispersed farm fields of a household are, the less its yield is different from the average yield of other households in the territory over years; (5) the field dispersion increases the inter-annual yield stability in a household (12 year simulation) but this relation depended on the rainfall data base used (6 years) and should be confirmed by further research on longer-term rainfall spatial data.

Chapter 7

Conclusions and perspectives

The main objective of this thesis was to provide the biophysical basis for the modeling of crop production in millet-based systems for decision support in the Sahelian Niger. The achievement of this objective required (1) a deep comprehension of the millet-based farming system, its assets and its constraints, (2) the choice of a proper crop-growth model, (3) a specific parameterization of millet cultivars and (4) a good performance of the model in reproducing the millet response to water x nutrient interaction. We made a thorough analysis of the millet-based system of Sahelian Niger based on its agronomic assets and constraints (except for biotic), the farmer soil fertility practices and the ones from research. This analysis of the millet-based agricultural system put in relation to the capabilities and performance of existing crop modeling frameworks made it possible to choose the APSIM model, although its counterpart DSSAT could have been equally adequate (chapter 2).

7.1 Characterization of Sahelian millet genotypes and APSIM model genetic parameterization

The APSIM-millet model being initially developed and validated for Indian millet cultivars, we had to parameterize and evaluate it for the cultivars, the climatic conditions, and the soil fertility practices of the Sahelian environment. First of all, we characterized the response of seven millet Sahelian cultivars to temperature and photoperiod under non-limiting water and nutrient supply conditions (chapter 3). In fact, the range of possible sowing dates in the Sahelian Niger is very wide, which makes the thermal and photoperiod conditions very variable from one sowing to another. This "sowing date" factor was then used to apprehend the response of seven cultivars to temperature and photoperiod at ICRISAT Sahelian center, Sadoré, Niger. The cultivars included three improved cultivars and four landraces chosen because they were the most frequently used by farmers in the three main agro-ecological zones of Niger (Fakara in the South-West, Maradi in the Southern center, and Zinder in the East). Our research showed that only one of the cultivars, Maewa, was very photosensitive contrary to the six others. The majority of the agronomic variables (leaf number, leaf area, biomass and grain yield) were negatively affected by late sowing (associated with lower air temperatures). This experiment, in particular, enabled us to calculate and to make available for the first time in the Sahel the principal eco-physiological or genetic parameters (thermal times of development phases, leaf area dynamics) for seven widely used varieties covering the whole range of possible sowing dates. Indeed obtaining these parameters requires expensive and time consuming experimentation, and their unavailability represented an important constraint for an extended use of dynamic crop modeling activities in millet-based systems in the Sahel. They were obtained for use in APSIM but are also applicable in other functionally similar models such as DSSAT.

7.2 Testing the APSIM model in various water and nutrient supply conditions under the Sahelian environment

To gain confidence for the use of the APSIM model for decision support in the Sahelian environment, we tested its performance (1) under non-limiting water and nutrient supply conditions and (2) under integrated nutrient management of millet in rainfed conditions.

The first step was to test the APSIM model on the same experiment that allowed the direct calculation of its genetic and eco-physiological parameters, i.e. the sowing date experiment under non-limiting water and nutrient supply conditions (chapter 3). The model could adequately reproduce the behavior in terms of phenology, development (leaf number and area index) and yield for six Sahelian millet genotypes. Taking into account the difference in leaf dynamics (time for leaf initiation TLI and appearance TLA) between cultivar and sowing dates due to temperature amplitude was decisive in the successful modeling exercise. The case of Maewa cultivar could not be handled by the APSIM model.

In a second step and following the calibration of soil water dynamics with an independent on-station experimental dataset, the APSIM model performed fairly well in predicting millet response to combined fertility management practices (millet residue, cattle manure and mineral fertilizer) for the CIVT Sahelian millet genotype under Sahelian environmental rainfed conditions (chapter 5). The model reproduced well the measured average plant available water PAW, the temporal LAI and aboveground biomass. The model was able to adequately reproduce the millet grain yield response trend to N inputs along with the water by nutrient interaction caused by the erratic rainfall conditions over years. We showed that the APSIM model may be used for decision support purposes in the Sahel regarding fertilizer and manure management for limited crop residue application rates ($\leq$ 900 kg ha^{-1}) and when P is supplied proportionately to the N.

7.3 Implications for millet-based systems improvement

We implemented two applications of our modeling experience by (1) supporting decision making regarding N management and (2) evaluating a commonly reported farmer agro-climatic risk coping strategy in the Fakara region of south-western Niger.

Combining soil fertility management practices (mineral fertilizer x manure), a 23-year, long-term factorial simulation with the validated model showed that moderate N application (15 kg N ha^{-1}) improves both the long term average and the yearly minimum guaranteed millet grain yield without increasing inter-annual variability compared to no N input. Despite the fact that it results in a lower long term average yield than the often recommended rate of 30 kg N ha^{-1}, we showed that the application of 15 kg N ha^{-1} is more appropriate for smallholder, subsistence farmers as far as it guarantees higher minimum yield in extreme dry years and lower inter-annual yield variability, thereby reducing farmer's vulnerability.

In the second model application, we integrated GIS information such as land tenure, weather data, fertility management and the process-based plant-growth APSIM model to test the hypothesis that farmers disperse their fields throughout the village territory to reduce the inter-annual yield variability in the Fakara region of Niger. The spatial and the temporal variability of rainfall would be the underlying reason of this behavior. We found that: (1) the spatial variability of annual rainfall induced an even higher spatial variability of millet production both at pixel and household levels; (2) the existence of a fertility gradient around villages increases the millet yield variability between households in a given territory; (3) the more dispersed the fields of a household are, the less its yield is different from the average of other households in the territory over years; (4) the field dispersion increases the inter-annual yield stability in a household (12 year simulation) but this relation depended on the rainfall data base used and should be confirmed by further research on longer-term rainfall spatial data.

7.4 Limitations of our research and perspectives

The limitations of our research are related to: (1) the dependence of leaf dynamics parameters on sowing date, (2) the APSIM failure to simulate the phenology of the very photosensitive Maewa landrace, (3) APSIM millet response to P and crop residue application (4) the evaluation of millet response to N for only the CIVT cultivar and without direct experimental measurement of N dynamics in the soil.

Leaf area dynamics (phyllochron and plastochron) was parameterized according to cultivar and sowing date (chapter 3). This was because, so far, most crop growth models, including APSIM, still lack physiological functionality to adequately match genotype x environment (G x E) interactions. These models emphasize the interaction between temperature (T) and photoperiod (P), but infer no physiological-genetic basis for the interaction (Ong and Everard, 1979; Yan and Wallace, 1998). Yan and Wallace (1998) proposed a genotype x temperature x photoperiod interaction GPT-model of phenology which performed better than P x T models. Further research should look at calibrating GPT-models of leaf dynamics for the Sahelian environment and possibly integrate them into the APSIM code.

For short day plants, models (CERES, APSIM) generally consider that the duration of the vegetative phase increases linearly with increasing daylength (juvenile phase). Such a linear function was shown to be inappropriate to simulate very photosensitive sorghum cultivars in Mali (Folliard *et al.*, 2004). And we ascribed this to be the reason why the APSIM model failed to simulate the photosensivity of the Maewa cultivar. Folliard *et al.* (2004) proposed a hyperbolic and a threshold hyperbolic function, with the last one performing better. Implementing such an approach in APSIM would help improve its capability in dealing with very photosensitive Sahelian landraces such as Maewa.

It is well known that P and N are the main limiting factors of millet production in the Nigerien Sahel. The INM experiment (chapter 4 and 5) we used assumed that enough P was provided proportionally to N supply and so no P deficiency was expected. Our work did not look at the simulation of millet response to P and this is a limitation. This resulted in the fact that the APSIM model could not reproduce the millet response to crop residue application (high amounts $\geq$ 900 kg ha^{-1}) because the generally positive effect of residue on millet growth in the Sahel has been attributed mainly to P mobility enhancement along with decrease in exchangeable Al and soil protection against wind erosion (Buerkert *et al.*, 2000). Soil-P module exists in the APSIM modelling framework and responds satisfactorily, for example, to other crops such as maize and sorghum (Probert, 2004; Kpongor, 2007) but not yet to millet. Further research works should tackle this shortcoming in collaboration with the APSIM development team.

The evaluation of the APSIM model with the INM experiment was done for a limited number of years (02) with only the CIVT improved cultivar at Sadoré site. Moreover we evaluated water x N interaction but no N measurement was done and the evaluation of N dynamics was considered in regards of expectations. Factorial and simpler N x P trials (preferably from mineral fertilizer) with the other 6 cultivars should help overcome this limitation. Such experiments should clearly measure N and P dynamics and be confronted with APSIM model simulations, and possibly target other soil types and regions.

Several other interesting and relevant applications of our modeling experience are possible in the Sahelian environment and we will just indicate a few hereafter.

It is common knowledge that the Sahel is highly vulnerable to climate change due its geographic location at the southern edge of the Sahara desert and the strong dependence of its population on rainfed agriculture (Kandji *et al.*, 2006). Study of the climate change impact on millet production, the staple crop in the area, is essential to foresee mitigation actions. Although few such studies have been reported in the Sahel, they estimate millet grain yield by means of empirical statistical models based only on climatic predictors (e.g. sea surface temperature anomalies, total rainfall in July, August, and September, number of rainy days; daily amount of rainfall, dry spells, maximum air temperature in the hottest month April; minimum air temperature in the coldest month January, etc) (Ben-Mohamed *et al.*, 2002). Our research showed that in addition to climate, cultivar and soil fertility management play a major and non negligible role in millet yield response. So coupling the APSIM model with weather generators for climate change scenario analysis integrating climate, cultivar and soil fertility managements would help to increase knowledge about the effective impact of climate change in the Sahelian environment.

Another possible APSIM application in the Sahelian environment may be in the framework of the "early warning system" for food crisis assessment and mitigation. So far, water balance - stress index models such as SARRA-H (Système d'Analyse Régional des Risques Agroclimatiques-Habillé) is extrapolated by AGRHYMET from plot to region using the DHC system ("Diagnostic Hydrique des Cultures") (Samba, 1998). The use of models like APSIM will be better for such application by integrating soil fertility management information and cultivar specificity according to agro-ecological region, knowing that these two factors cannot be omitted in the Sahelian millet-based system. Moreover combining APSIM model and remote sensing will improve regional yield predictions by accurately integrating for instance (from remote sensing), the exact area cropped, and differences in sowing dates. Moreover, key agronomic state variables such as biomass and LAI could be derived from remote sensing and serve to improve APSIM predictions. These methods have already been successfully applied elsewhere for instance in the Netherlands (Jongschaap, 2006).

The final step in decision support is to gather biophysical tools with social and economic ones in a decision support system (DSS) to allow an in depth and integrated analysis of the millet-based agricultural system. DSS should also serve as a tool for the interactive identification with the stakeholders of the most promising soil water and fertility management options for instance. For this goal, the use of complex crop growth simulation models as APSIM is not realistic, because such models are complex, and hardware requirements and computation time are high and generally beyond the capability of technology-transfer specialists. Metamodels constitute an alternative to the use of complex numerical models (Brooks *et al.*, 2001; Hussain *et al.*, 2002; Garcet *et al.*, 2006). Such models, which are in fact a model of a model, use statistically significant relationships built from input-output data derived from complex models, thereby strongly reducing the computation and parameterization requirements. Further research should look at ways to simplify the APSIM model into metamodels for integration into a broader DSS.

Bibliography

Abdoulaye, T. and Lowenberg-Deboer, J. 2000. Intensification of Sahelian Farming Systems: Evidence From Niger. *Agricultural Systems*, 64:67–81.

Abdoulaye, T. and Sanders, J. H. 2005. Stages and Determinants of Fertilizer Use in Semiarid African Agriculture: the Niger Experience. *Agricultural Economics*, 32:167–179.

Adomou, M., Prasad, P. V. V., Boote, K. J., and Detongnon, J. 2005. Disease assessment methods and their use in simulating growth and yield of peanut crops affected by leafspot disease. *Annals of Applied Biology*, 146:469–479.

Affholder, F. 1997. Empirically modelling the interaction between intensification and climatic risk in semiarid regions. *Field Crops Research*, 52:79–93.

Ahmed, M. M., Sanders, J. H., and Nell, W. T. 2000. New Sorghum and Millet Cultivar Introduction in Sub-Saharan Africa: Impacts and Research Agenda. *Agricultural Systems*, 64:55–65.

Akponikpè, P. B. I. 2005. Monitoring farmers fields to access the impact of fertility management practices on pearl millet production in the Fakara region, Niger. Working paper. UCL/ICRISAT. 9p.

Akponikpè, P. B. I., Bielders, C. L., Gérard, B., and Michels, K. 2006. Simulation of millet response to combined application of cattle manure, millet residue and chemical fertilizer in the Sahel using APSIM. In Agricultural Research Western Australia, editor, *"Groundbreaking stuff". Proceedings of the 13th Australian Society of Agronomy Conference*. ASA, Perth, Australia.

Akponikpè, P. B. I., Bielders, C. L., Gérard, B., and Michels, K. 2007. Modelling integrated fertility management strategies for pearl millet in the Sahel. In Neve, S. D., Salomez, J., Bossche, A. V., Haneklaus, S., Cleemput, O. V., Hofman, G., and Schnug, E., editors, *Mineral versus organic fertilizer: conflict or synergism? Proceedings of the 16th international symposium of the international scientific centre for fertilizers*. CIEC, Gent, Belgium.

Akponikpè, P. B. I., Michels, K., and Bielders, C. L. 2008. Integrated nutrient management of pearl millet in the Sahel using combined application of cattle manure, crop residues and mineral fertilizer. *Experimental Agriculture, in press*.

Alagarswamy, G. and Ritchie, J. T. 1991. Phasic development in CERES-Sorghum model. In Hodges, T., editor, *Predicting crop phenology*, pages 143–152. Boca Raton, FL, CRC Press.

Azam-Ali, S. N., Gregory, P. J., and Monteith, J. L. 1984. Effects of planting density on water use and productivity of pearl millet (Pennisetum typhoides) grown on stored water I: growth of roots and shoots. *Experimental agriculture*, 20:203–214.

Bacci, L., Cantini, C., Pierini, F., Maracchi, G., and Reyniers, F. N. 1999. Effects of Sowing Date and Nitrogen Fertilization on Growth, Development and Yield of a Short Day Cultivar of Millet (Pennisetum Glaucum L.) In Mali. *European Journal of Agronomy*, 10:9–21.

Badini, O., Stockle, C. O., and Franz, E. H. 1997. Application of Crop Simulation Modeling and Gis to Agroclimatic Assessment in Burkina Faso. *Agriculture Ecosystems & Environment*, 64:233–244.

Badini, O., Stockle, C. O., Jones, J. W., Nelson, R., Kodio, A., and Keita, M. 2007. A Simulation-Based Analysis of Productivity and Soil Carbon in Response to Time-Controlled Rotational Grazing in the West African Sahel Region. *Agricultural Systems*, 94-1:87–96.

Bagayoko, M., Buerkert, A., Lung, G., Bationo, A., and Romheld, V. 2000. Cereal/Legume Rotation Effects on Cereal Growth in Sudano-Sahelian West Africa: Soil Mineral Nitrogen, Mycorrhizae and Nematodes. *Plant and Soil*, 218:103–116.

Baidu-Forson, J. 1995. Determinants of the availability of adequate millet stover for mulching in the Sahel. *Journal of Sustainable Agriculture*, 5:101–116.

Baron, C., Reyniers, F., Clopes, A., and Forest, F. 1999. Applications du logiciel SARRA a l'étude de risques climatiques. *Agriculture et Développement*, 24:89–97.

Baron, C., Sultan, B., Balme, M., Sarr, B., Traoré, S., Lebel, T., Janicot, S., and Dingkuhn, M. 2005. From GCM Grid Cell to Agricultural Plot: Scale Issues Affecting Modelling of Climate Impact. *Philosophical Transactions of the Royal Society B-Biological Sciences*, 360:2095–2108.

Bationo, A. and Buerkert, A. 2001. Soil Organic Carbon Management for Sustainable Land Use in Sudano-Sahelian West Africa. *Nutrient Cycling in Agroecosystems*, 61:131–142.

Bationo, A. and Mokwunye, A. U. 1991a. Alleviating Soil Fertility Constraints to Increased Crop Production in West Africa - the Experience in the Sahel. *Fertilizer Research*, 29:95–115.

Bationo, A. and Mokwunye, A. U. 1991b. Role of manures and crop residue in alleviating soil fertility constraints to crop production: With special reference to the Sahelian and Sudanian zones of West Africa. *Fertilizer Research*, 29:117–125.

Bationo, A. and Ntare, B. R. 2000. Rotation and Nitrogen Fertilizer Effects on Pearl Millet, Cowpea and Groundnut Yield and Soil Chemical Properties in a Sandy Soil in the Semi-Arid Tropics, West Africa. *Journal of Agricultural Science*, 134:277–284.

Bationo, A., Chien, S. H., Henao, J., Christianson, B. C., and Mokwunye, A. U. 1990a. Agronomic evaluation of two unacidulated and partially acidulated phosphate rocks indigenous to Niger. *Soil Science Society of America Journal*, 54:1772–1777.

Bationo, A., Christianson, C. B., and Baethgen, W. E. 1990b. Plant-Density and Nitrogen-Fertilizer Effects on Pearl-Millet Production in Niger. *Agronomy Journal*, 82:290–295.

Bationo, A., Christianson, C. B., Baethgen, W. E., and Mokwunye, A. U. 1992. A Farm-Level Evaluation of Nitrogen and Phosphorus-Fertilizer Use and Planting Density for Pearl-Millet Production in Niger. *Fertilizer Research*, 31:175–184.

Bationo, A., Christianson, C. B., and Klaij, M. C. 1993. The Effect of Crop Residue and Fertilizer Use on Pearl-Millet Yields in Niger. *Fertilizer Research*, 34:251–258.

Bationo, A., Buerkert, A., Sedogo, M. P., Christianson, B. C., and Mokwunye, A. U. 1995. A critical review of crop-residue use as soil amendment in the west African semi-arid tropics. In Powell, J. M., Fernandez-Rivera, S., Williams, T. O., and Renard, C., editors, *Livestock and sustainable nutrient cycling in mixed farming systems of sud-Saharan Africa. Vol II: technical papers, Proceedings of an international conference held in Addis Abeba, Ethiopia, 22-26 Nov 1993*, pages 305–322. ILCA, SGPR.

Bationo, A., Lompo, F., and Koala, S. 1998. Research on Nutrient Flows and Balances in West Africa: State-of-the-Art. *Agriculture Ecosystems & Environment*, 71:19–35.

Bationo, A., Mokwunye, U., Vlek, P. L. G., Koala, S., and Shapiro, B. I. 2003. Soil fertility management for sustainable land use in the West African Sudano-Sahelian zone. In Gichuri, M. P., Bationo, A., Bekunda, M. A., Goma, H. C., Mafongoya, P. L., Mugendi, D. N., Murwuira, H. K., Nandwa, S. M., Nyathi, P., and Swift, M. J., editors, *Soil fertility management in Africa: A regional perspective*, pages 253–292. Academy Science Publishers (ASP); Centro Internacional de Agricultura Tropical (CIAT); Tropical Soil Biology and Fertility (TSBF), Nairobi, Kenya.

Bazi, H., Sanou, A., Verberne, E., Jongschaap, R., Dijksterhuis, G., and Bonzi, M. 1995. Manuel du logiciel interactif (CP-BKF3): sorgho, mil et mais. Note 20. DLO Institute for Agrobiology and Soil Fertility Research (AB-DLO), Haren/Wageningen, the Netherlands. 29p.

Bechini, L., Bocchi, S., and Maggiore, T. 2003. Spatial Interpolation of Soil Physical Properties for Irrigation Planning. A Simulation Study in Northern Italy. *European Journal of Agronomy*, 19:1–14.

Ben-Mohamed, A., Duivenbooden, N. V., and Abdoussallam, S. 2002. Impact of Climate Change on Agricultural Production in the Sahel - Part 1. Methodological Approach and Case Study for Millet in Niger. *Climatic Change*, 54:327–348.

Bielders, C. L. and Michels, K. 2002. On-Farm Evaluation of Ridging and Residue Management Options in a Sahelian Millet-Cowpea Intercrop. 2. Crop Development. *Soil Use and Management*, 18:309–315.

Bielders, C. L., Michels, K., and Rajot, J. L. 2000. On-Farm Evaluation of Ridging and Residue Management Practices to Reduce Wind Erosion in Niger. *Soil Science Society of America Journal*, 64:1776–1785.

Bielders, C. L., Lamers, J. P. A., and Michels, K. 2001. Wind Erosion Control Technologies in the West African Sahel: the Effectiveness of Windbreaks, Mulching and Soil Tillage, and the Perspective of Farmers. *Annals of Arid Zone*, 40:369–394.

Bielders, C. L., Michels, K., and Bationo, A. 2002. On-Farm Evaluation of Ridging and Residue Management Options in a Sahelian Millet-Cowpea Intercrop. 1. Soil Quality Changes. *Soil Use and Management*, 18:216–222.

Birch, C. J., Hammer, G. L., and Rickert, K. G. 1998a. Temperature and photoperiod sensitivity of development in five cultivars of maize (Zea mays L.) from emergence to tassel initiation. *Field Crops Research*, 55:93–107.

Birch, C. J., Vos, J., Kiniry, J., Bos, H. J., and Elings, A. 1998b. Phyllochron responds to acclimation to temperature and irradiance in maize. *Field Crops Research*, 59:187–200.

Bishop, M. A. 2007. Point pattern analysis of eruption points for the Mount Gambier volcanic sub-province: a quantitative geographical approach to the understanding of volcano distribution. *Area*, 39:230–241.

Bley, J., Ploeg, R. R. V. D., Sivakumar, M. V. K., and Allison, B. E. 1991. A risk-probability map for millet production in southwest Niger. *IAHS Publication (International Association of Hydrological Sciences)*, pages 571–581.

Bouman, B. A. M., Vankeulen, H., Vanlaar, H. H., and Rabbinge, R. 1996. The 'school of De Wit' Crop Growth Simulation Models: a Pedigree and Historical Overview. *Agricultural Systems*, 52:171–198.

Brisson, N., Gary, C., Justes, E., Roche, R., Mary, B., Ripoche, D., Zimmer, D., Sierra, J., Bertuzzi, P., Burger, P., Bussiere, F., Cabidoche, Y. M., Cellier, P., Debaeke, P., Gaudillere, J. P., Henault, C., Maraux, F., Seguin, B., and Sinoquet, H. 2003. An Overview of the Crop Model Stics. *European Journal of Agronomy*, 18:309–332.

Brooks, R. J., Semenov, M. A., and Jamieson, P. D. 2001. Simplifying Sirius: Sensitivity Analysis and Development of a Meta-Model for Wheat Yield Prediction. *European Journal of Agronomy*, 14:43–60.

Brouwer, J. and Powell, J. M. 1998. Increasing Nutrient Use Efficiency in West-African Agriculture: the Impact of Micro-Topography on Nutrient Leaching From Cattle and Sheep Manure. *Agriculture Ecosystems & Environment*, 71:229–239.

Brouwer, J., Fussell, L. K., and Herrmann, L. 1993. Soil and Crop Growth Microvariability in the West-African Semiarid Tropics - a Possible Risk-Reducing Factor for Subsistence Farmers. *Agriculture Ecosystems & Environment*, 45:229–238.

Buerkert, A. and Hiernaux, P. 1998. Nutrients in the West African Sudano-Sahelian Zone: Losses, Transfers and Role of External Inputs. *Zeitschrift Fur Pflanzenernahrung Und Bodenkunde*, 161:365–383.

Buerkert, A. and Lamers, J. P. A. 1999. Soil Erosion and Deposition Effects on Surface Characteristics and Pearl Millet Growth in the West African Sahel. *Plant and Soil*, 215:239–253.

Buerkert, A. and Stern, R. D. 1995. Effects of Crop Residue and Phosphorus Application on the

Spatial Variability of Nondestructively Measured Millet Growth in the Sahel. *Experimental Agriculture*, 31:429–449.

Buerkert, A., Bationo, A., and Dossa, K. 2000. Mechanisms of Residue Mulch-Induced Cereal Growth Increases in West Africa. *Soil Science Society of America Journal*, 64:346–358.

Buerkert, A., Bationo, A., and Piepho, H. P. 2001. Efficient Phosphorus Application Strategies for Increased Crop Production in Sub-Saharan West Africa. *Field Crops Research*, 72:1–15.

Buerkert, A., Piepho, H. P., and Bationo, A. 2002. Multi-Site Time-Trend Analysis of Soil Fertility Management Effects on Crop Production in Sub-Saharan West Africa. *Experimental Agriculture*, 38:163–183.

Caddel, J. L. and Weibel, D. E. 1972. Photoperiodism in Sorghum. *Agronomy Journal*, 64-4:473–476.

Carberry, P. S. and Campbell, L. C. 1985. The growth and development of pearl millet as affected by photoperiod. *Field Crops Research*, 11:207–217.

Chappell, A. and Agnew, C. T. 2004. Modelling Climate Change in West African Sahel Rainfall (1931-90) as an Artifact of Changing Station Locations. *International Journal of Climatology*, 24:547–554.

Chivenge, P., Dimes, J., Nhamo, N., Nzuma, J. K., and Murwira, H. K. 2004. Evaluation of APSIM to simulate maize response to manure inputs in wet and dry regions of Zimbabwe. In Delve, R. J. and Probert, M. E., editors, *Modelling nutrient management in tropical cropping systems*, pages 85–91. Canberra, Australian Center for International Agricultural Research (ACIAR) No 114.

Christakos, G., Bogaert, P., and Serre, M. L. 2002. *Temporal GIS. Advanced Functions for Field-Based Applications*. Springer-Verlag, New York NY. 250p.

Christianson, C. B., Bationo, A., Henao, J., and Vlek, P. L. G. 1990. Fate and Efficiency of N-Fertilizers Applied to Pearl-Millet in Niger. *Plant and Soil*, 125:221–231.

CLIMAG-WA. 2002. Harmonisation of climate prediction for mitigation of global change impact in Sudano-Sahelian west-Africa. volume Proceedings of an international workshop. CLIMAG-West Africa, Plant Research International (Netherlands), Institut d'Économie Rurale (Mali), ICRISAT (Mali), START (USA).

Coaldrake, P. D. 1985. Leaf area accumulation of pearl millet as affected by nitrogen supply. *Field Crops Research*, 11:185–192.

Coaldrake, P. D. and Pearson, C. J. 1985. Development and dry weight accumulation of pearl millet as affected by nitrogen supply. *Field Crops Research*, 11:171–184.

Coaldrake, P. D. and Pearson, C. J. 1986. Environmental Influences on Panicle Differentiation and Spikelet Number of Pennisetum americanum. *Journal of Experimental Botany*, 37:865–875.

Craufurd, P. Q., Mahalakshmi, V., Bidinger, F. R., Mukuru, S. Z., Chantereau, J., Omanga, P. A., Qi, A., Roberts, E. H., Ellis, R. H., Summerfield, R. J., and Hammer, G. L. 1999. Adaptation of Sorghum: Characterisation of Genotypic Flowering Responses to Temperature and Photoperiod. *Theoretical and Applied Genetics*, 99:900–911.

Dai, A. G., Lamb, P. J., Trenberth, K. E., Hulme, M., Jones, P. D., and Xie, P. P. 2004. The Recent Sahel Drought Is Real. *International Journal of Climatology*, 24:1323–1331.

Dandois Dutordoir, C. 2006. Impact de pratiques de gestion de la fertilité sur les rendements en mil dans le Fakara (Niger). Mémoire de Bio-Ingénieur. Faculté d'Ingénierie biologique, agronomique et environnementale. Université catholique de Louvain, Belgique. 162p + annexes.

De Rouw, A. 2004. Improving Yields and Reducing Risks in Pearl Millet Farming in the African Sahel. *Agricultural Systems*, 81:73–93.

De Rouw, A. and Rajot, J. L. 2004a. Nutrient Availability and Pearl Millet Production in Sahelian Farming Systems Based on Manuring or Fallowing. *Agriculture Ecosystems & Environment*, 104:249–262.

De Rouw, A. and Rajot, J. L. 2004b. Soil Organic Matter, Surface Crusting and Erosion in Sahelian Farming Systems Based on Manuring or Fallowing. *Agriculture Ecosystems & Environment*, 104:263–276.

D'Herbes, J. M. and Valentin, C. 1997. Land Surface Conditions of the Niamey Region: Ecological and Hydrological Implications. *Journal of Hydrology*, 189:18–42.

Dingkuhn, M., Singh, B. B., Clerget, B., Chantereau, J., and Sultan, B. 2006. Past, present and future criteria to breed crops for water-limited environments in West Africa: Special Issue on Water Scarcity: Challenges and Opportunities for Crop Science. *Agricultural Water Management*, 80:241–261.

Do, F., Winkel, T., Cournac, L., and Louguet, P. 1996. Impact of Late-Season Drought on Water Relations in a Sparse Canopy of Millet (Pennisetum Glaucum (L) R Br). *Field Crops Research*, 48:103–113.

Doherty, J. 2004. PEST Model-Independent Parameter Estimation. User's Manual 5th Edition. page 147p. Watermark Numerical Computing, Brisbane Australia.

Doorenbos, J. and Pruitt, W. O. 1977. Crop Water Requirements. FAO Irrigation and Drainage Paper No. 24. FAO, Rome. 94p.

Dourado-Neto, D., Teruel, D. A., Reichardt, K., Nielsen, D. R., Frizzone, J. A., and Bacchi, O. O. S. 1998a. Principles of crop modeling and simulation: I. uses of mathematical models in agricultural science. *Scientia Agricola Piracicaba*, 55:46–50.

Dourado-Neto, D., Teruel, D. A., Reichardt, K., Nielsen, D. R., Frizzone, J. A., and Bacchi, O. O. S. 1998b. Principles of crop modeling and simulation: II. The implication of objectives in model development. *Scientia Agricola Piracicaba*, 55:51–57.

Dugué, P. C. 1998. Gestion de la fertilite et strategies paysannes. Le cas des zones de savanes d'Afrique de l'Ouest et du centre. *Agriculture et Developpement*, 18:13–20.

Dupisani, A. I. 1987. The Ceres-Maize Model as a Potential Tool for Drought Assessment in South-Africa. *Water Sa*, 13:159–164.

Enyong, L. A., Debrah, S. K., and Bationo, A. 1999. Farmers' Perceptions and Attitudes Towards Introduced Soil-Fertility Enhancing Technologies in Western Africa. *Nutrient Cycling in Agroecosystems*, 53:177–187.

Esse, P. C., Buerkert, A., Hiernaux, P., and Assa, A. 2001. Decomposition of and Nutrient Release From Ruminant Manure on Acid Sandy Soils in the Sahelian Zone of Niger, West Africa. *Agriculture Ecosystems & Environment*, 83:55–63.

FAO. 2007. FAOSTAT Database on Agriculture http://faostat.fao.org/.

Fatondji, D. 2002. *Organic amendment decomposition, nutrient release and nutrient uptake by millet (Pennisetum glaucum L. R. Br) in a traditional land rehabilitation technique (zai) in the Sahel. Ecology and development Series No. 1*. Ph.D. thesis, University of Bonn. 147p.

Fatondji, D., Martius, C., Bielders, C. L., Vlek, P. L. G., Bationo, A., and Gérard, B. 2006. Effect of Planting Technique and Amendment Type on Pearl Millet Yield, Nutrient Uptake, and Water Use on Degraded Land in Niger. *Nutrient Cycling in Agroecosystems*, 76:203–217.

Fechter, J. 1993. *The simulation of pearl millet (Pennisetum glaucum L.) growth under the environmental conditions of southwestern Niger, West Africa*. Ph.D. thesis, Universitaat Hohenheim, Institute fur Bodenkunde und Standorslehre. 121p.

Fechter, J., Allison, B. E., Sivakumar, M. V. K., Ploeg, R. R. V. D., and Bley, J. 1991. Evaluation of the SWATRER and CERES-Millet models for southwest Niger. *IAHS Publication*

(International Association of Hydrological Sciences), pages 505–513.

Folliard, A., Traoré, P. C. S., Vaksmann, M., and Kouressy, M. 2004. Modeling of sorghum response to photoperiod: a threshold-hyperbolic approach. *Field Crops Research*, 89:59–70.

Fussell, L. K., Serafini, P. G., Bationo, A., and Klaij, M. C. 1987. Management practices to increase yield and yield stability of pearl millet in Africa. In *International Pearl Millet workshop. Proceedings of an international workshop*. ICRISAT, Patancheru, AP, India. pp255-268.

Gandah, M., Stein, A., Brouwer, J., and Bouma, J. 2000. Dynamics of Spatial Variability of Millet Growth and Yields at Three Sites in Niger, West Africa and Implications for Precision Agriculture Research. *Agricultural Systems*, 63:123–140.

Gandah, M., Bouma, J., Brouwer, J., Hiernaux, P., and Duivenbooden, N. V. 2003a. Strategies to Optimize Allocation of Limited Nutrients to Sandy Soils of the Sahel: a Case Study From Niger, West Africa. *Agriculture Ecosystems & Environment*, 94:311–319.

Gandah, M., Brouwer, J., Hiernaux, P., and Duivenbooden, N. V. 2003b. Fertility Management and Landscape Position: Farmers' Use of Nutrient Sources in Western Niger and Possible Improvements. *Nutrient Cycling in Agroecosystems*, 67:55–66.

Garcet, J. D. P., Ordonez, A., Roosen, J., and Vanclooster, M. 2006. Metamodelling: Theory, concepts and application to nitrate leaching modelling. *Ecological Modelling*, 193:629–644.

Geiger, S. C. and Manu, A. 1993. Soil Surface Characteristics and Variability in the Growth of Millet in the Plateau and Valley Region of Western Niger. *Agriculture Ecosystems & Environment*, 45:203–211.

Geiger, S. C., Manu, A., and Bationo, A. 1992. Changes in a Sandy Sahelian Soil Following Crop Residue and Fertilizer Additions. *Soil Science Society of America Journal*, 56:172–177.

Geiger, S. C., Vandenbeldt, R. J., and Manu, A. 1994. Variability in the Growth of Faidherbia-Albida - the Soils Connection. *Soil Science Society of America Journal*, 58:227–231.

Gijsman, A. J., Hoogenboom, G., Parton, W. J., and Kerridge, P. C. 2002. Modifying DSSAT Crop Models for Low-Input Agricultural Systems Using a Soil Organic Matter-Residue Module from CENTURY. *Agronomy Journal*, 94:462–474.

Graef, F. 2000. Agroclimatology in southwestern Niger - Implication for crop growth and crop management. In Graef, F., Lawrence, P., and von Oppen, M., editors, *Adapted farming in West Africa: Issues, potentials and perspectives*, pages 27–31. Verlag Ulrich E. Grauer, Stuttgart, Germany.

Graef, F. and Haigis, J. 2001. Spatial and Temporal Rainfall Variability in the Sahel and Its Effects on Farmers' Management Strategies. *Journal of Arid Environments*, 48:221–231.

Gérard, B. and Buerkert, A. 1999. Aerial Photography to Determine Fertiliser Effects on Pearl Millet and Guiera Senegalensis Growth. *Plant and Soil*, 210:167–177.

Gérard, B. and Buerkert, A. 2001. Estimation of Spatial Variability in Pearl Millet Growth With Non-Destructive Methods. *Experimental Agriculture*, 37:373–389.

Gregory, P. J. 1986. Response to Temperature in a Stand of Pearl-Millet (Pennisetum typhoides-S and Pennisetum typhoides-H). 8. Root-Growth. *Journal of Experimental Botany*, 37:379–388.

Hafner, H., Bley, J., Bationo, A., Martin, P., and Marschner, H. 1993a. Long-Term Nitrogen-Balance for Pearl-Millet (Pennisetum-Glaucum L) in an Acid Sandy Soil of Niger. *Zeitschrift Fur Pflanzenernahrung Und Bodenkunde*, 156:169–176.

Hafner, H., George, E., Bationo, A., and Marschner, H. 1993b. Effect of Crop Residues on Root-Growth and Phosphorus Acquisition of Pearl-Millet in an Acid Sandy Soil in Niger. *Plant and Soil*, 150:117–127.

Hammer, G. L., Rickert, K. G., and Birch, C. J. 1998. Improved methods for predicting individual leaf area and leaf senescence in maize (Zea mays). *Australian Journal of Agricultural Research*, 49(2):249–262.

Harris, F. 2002. Management of Manure in Farming Systems in Semi-Arid West Africa. *Experimental Agriculture*, 38:131–148.

Hatfield, J. L., Sauer, T. J., and Prueger, J. H. 2001. Managing Soils to Achieve Greater Water Use Efficiency: A Review. *Agronomy Journal*, 93:271–280.

Hiernaux, P. and Ayantunde, A. 2004. The Fakara: a semi-arid agro-ecosystem under stress. Report of research activities. page 95p. ILRI/DMP, Niamey, Niger.

Hoogmoed, W. B. and Klaij, M. C. 1990. Soil-Management for Crop Production in the West African Sahel .1. Soil and Climate Parameters. *Soil & Tillage Research*, 16:85–103.

Hoogmoed, W. B. and Stroosnijder, L. 1984. Crust Formation on Sandy Soils in the Sahel .1. Rainfall and Infiltration. *Soil & Tillage Research*, 4:5–23.

Hulme, M. 2001. Climatic perspectives on Sahelian desiccation: 1973-1998. *Global Environmental Change*, 11:19–29.

Hunt, B. G. 2000. Natural climatic variability and Sahelian rainfall trends. *Global and Planetary Change*, 24:107–131.

Hussain, M. F., Barton, R. R., and Joshi, S. B. 2002. Metamodeling: Radial Basis Functions, Versus Polynomials. *European Journal of Operational Research*, 138:142–154.

INRAN. 1990. Rapport d'activité agronomie générale, campagne 1989/1990, Institut de Recherche Agronomique du Niger - Niger, BP 429 Niamey, Niger.

Jagtap, S. S., Abamu, F. J., and Kling, J. G. 1999. Long-term assessment of nitrogen and variety technologies on attainable maize yields in Nigeria using CERES-maize. *Agricultural Systems*, 60:77–86.

Jones, J. W., Hoogenboom, G., Porter, C. H., Boote, K. J., Batchelor, W. D., Hunt, L. A., Wilkens, P. W., Singh, U., Gijsman, A. J., and Ritchie, J. T. 2003. The Dssat Cropping System Model. *European Journal of Agronomy*, 18:235–265.

Jones, P. G. and Thornton, P. K. 2002. Spatial modeling of risk in natural resource management. *Conservation ecology*, 5:27. [online] URL: http://www.consecol.org/vol5/iss2/art27/.

Jongschaap, R. E. E. 2006. *Integrating crop growth simulation and remote sensing to improve resource use efficiency in farming systems*. Ph.D. thesis, Wageningen University. 130p.

Kamel, A., Schroeder, K., Sticklen, J., Rafea, A., Salah, A., Schulthess, U., Ward, R., and Ritchie, J. 1995. Integrated wheat crop management based on generic task knowledge-based systems and CERES numerical simulation. *AI Applications*, 9:17–28.

Kandji, S. T., Verchot, L., and Mackensen, J. 2006. *Climate change and variability in the Sahel region: impact and adaptation strategies in the agricultural sector*. ICRAF-UNEP, Nairobi, Kenya. 58p.

Keating, B. A., Carberry, P. S., Hammer, G. L., Probert, M. E., Robertson, M. J., Holzworth, D., Huth, N. I., Hargreaves, J. N. G., Meinke, H., Hochman, Z., Mclean, G., Verburg, K., Snow, V., Dimes, J. P., Silburn, M., Wang, E., Brown, S., Bristow, K. L., Asseng, S., Chapman, S., Mccown, R. L., Freebairn, D. M., and Smith, C. J. 2003. An Overview of Apsim, a Model Designed for Farming Systems Simulation. *European Journal of Agronomy*, 18:267–288.

Kimani, S. K., Nandwa, S. M., Mugendi, D. N., Obanyi, S. N., Ojiem, J., Murwira, H. K., and Bationo, A. 2003. Principles of integrated soil fertility management. In Gichuri, M. P., Bationo, A., Bekunda, M. A., Goma, H. C., Mafongoya, P. L., Mugendi, D. N., Murwuira, H. K., Nandwa, S. M., Nyathi, P., and Swift, M. J., editors, *Soil fertility management in Africa: A regional perspective*, pages 51–72. Academy Science Publishers (ASP); Centro Internacional de Agricultura Tropical (CIAT); Tropical Soil Biology and Fertility (TSBF), Nairobi, Kenya.

Kimetu, J. M., Mugendi, D. N., Palm, C. A., Mutuo, P. K., Gachengo, C. N., Bationo, A., Nandwa, S., and Kungu, J. B. 2004. Nitrogen Fertilizer Equivalencies of Organics of Differing Quality and Optimum Combination With Inorganic Nitrogen Source in Central Kenya. *Nutrient Cycling in Agroecosystems*, 68:127–135.

Kinyangi, R. J., Delve, J., and Probert, M. E. 2004. Testing the APSIM model with data from a phosphorus and nitrogen replenishment experiment on an Oxisol in Western Kenya. In Delve, R. J. and Probert, M. E., editors, *Modelling nutrient management in tropical cropping systems*, pages 101–109. Canberra, Australian Center for International Agricultural Research (ACIAR) No 114.

Klaij, M. C. and Ntare, B. R. 1995. Rotation and Tillage Effects on Yield of Pearl-Millet (Pennisetum-Glaucum) and Cowpea (Vigna-Unguiculata), and Aspects of Crop Water-Balance and Soil Fertility in a Semiarid Tropical Environment. *Journal of Agricultural Science*, 124:39–44.

Klaij, M. C. and Vachaud, G. 1992. Seasonal Water-Balance of a Sandy Soil in Niger Cropped With Pearl-Millet, Based on Profile Moisture Measurements. *Agricultural Water Management*, 21:313–330.

Klaij, M. C., Renard, C., and Reddy, K. C. 1994. Low-Input Technology Options for Millet-Based Cropping Systems in the Sahel. *Experimental Agriculture*, 30:77–82.

Kpongor, D. S. 2007. *Spatially explicit modeling of sorghum (Sorghum bicolor (L.) Moench) production on complex terrain of a semi-arid region in Ghana using APSIM. Ecology and development Series No. 51*. Ph.D. thesis, University of Bonn. 142p.

Kretzschmar, R. M., Hafner, H., Bationo, A., and Marschner, H. 1991. Long-Term and Short-Term Effects of Crop Residues on Aluminum Toxicity, Phosphorus Availability and Growth of Pearl-Millet in an Acid Sandy Soil. *Plant and Soil*, 136:215–223.

Lamers, J., Bruentrup, M., and Buerkert, A. 1998. The Profitability of Traditional and Innovative Mulching Techniques Using Millet Crop Residues in the West African Sahel. *Agriculture Ecosystems & Environment*, 67:23–35.

Lamers, J. P. A. and Feil, P. R. 1995. Farmers' Knowledge and Management of Spatial Soil and Crop Growth Variability in Niger, West Africa. *Netherlands Journal of Agricultural Science*, 43:375–389.

Laws Agricultual Trust. 2002. *GenStat for Windows, Release 6.1, 6th edn.*. VSN International Ltd., Oxford, UK.

Le Barbé, L. and Lebel, T. 1997. Rainfall climatology of the HAPEX-Sahel region during the years 1950-1990. *Journal of Hydrology*, 188-189:43–73.

Lebel, T., Taupin, J. D., and D'Amato, N. 1997. Rainfall monitoring during HAPEX-Sahel. 1. General rainfall conditions and climatology. *Journal of Hydrology*, 188-189:74–96.

L'hote, Y., Mahe, G., Some, B., and Triboulet, J. P. 2002. Analysis of a Sahelian Annual Rainfall Index From 1896 to 2000; the Drought Continues. *Hydrological Sciences Journal-Journal Des Sciences Hydrologiques*, 47:563–572.

L'hote, Y., Mahe, G., and Some, B. 2003. Reply to "the Sahelian Drought May Have Ended During the 1990s" the 1990s Rainfall in the Sahel: the Third Driest Decade Since the Beginning of the Century. *Hydrological Sciences Journal-Journal Des Sciences Hydrologiques*, 48:493–496.

Loague, K. and Green, R. E. 1991. Statistical and graphical methods for evaluating solute transport models: Overview and application. *Journal of Contaminant Hydrology*, 7:51–73.

Lu, H. Y., Lu, C. T., Wei, M. L., and Chan, L. F. 2004. Comparison of Different Models for Nondestructive Leaf Area Estimation in Taro. *Agronomy Journal*, 96:448–453.

Macrobert, J. F. and Savage, M. J. 1998. The Use of a Crop Simulation Model for Planning Wheat Irrigation in Zimbabwe. *Understanding options for agricultural production*, pages 205–220.

Maiti, R. K. and Bidinger, F. R. 1981. Growth and development of the pearl millet plant. Research Bulletin no. 6. page 14p. Patancheru, A.P. , India: Internationational Crops Research Institute for the Semi-Arid Tropics.

Manu, A., Bationo, A., and Geiger, S. C. 1991. Fertility Status of Selected Millet Producing Soils of West Africa With Emphasis on Phosphorus. *Soil Science*, 152:315–320.

Manu, A., Pfordresher, A. A., Geiger, S. C., Wilding, L. P., and Hossner, L. R. 1996. Soil Parameters Related to Crop Growth Variability in Western Niger, West Africa. *Soil Science Society of America Journal*, 60:283–288.

Mathworks, T. 2007. *Matlab and Simuling Release note R2007b*. The Mathworks, Michigan, USA.

Mbabaliye, T. and Wojtkowski, P. A. 1994. Problems and Perspectives on the Use of a Crop Simulation-Model in an African Research Station. *Experimental Agriculture*, 30:441–446.

Mccown, R. L., Hammer, G. L., Hargreaves, J. N. G., Holzworth, D. P., and Freebairn, D. M. 1996. Apsim: a Novel Software System for Model Development, Model Testing and Simulation in Agricultural Systems Research. *Agricultural Systems*, 50:255–271.

Michels, K. and Bielders, C. L. 2006. Pearl Millet Growth on an Erosion-Affected Soil in the Sahel. *Experimental Agriculture*, 42:1–17.

Michels, K., Sivakumar, M. V. K., and Allison, B. E. 1995. Wind Erosion Control Using Crop Residue. 2. Effects on Millet Establishment and Yields. *Field Crops Research*, 40:111–118.

Micheni, A. N., Kihanda, F. M., Warren, G. P., and Probert, M. E. 2004. Testing the APSIM model with experiment data from the long term manure experiment at Machang'a (Embu), Kenya. In Delve, R. J. and Probert, M. E., editors, *Modelling nutrient management in tropical cropping systems*, pages 110–117. Canberra, Australian Center for International Agricultural Research (ACIAR) No 114.

Miedema, R., Brouwer, J., Geiger, S. C., and Vandenbeldt, R. J. 1994. Variability in the growth of Faidherbia albida near Niamey, Niger, Africa: macromorphology aspects of termites activity. In Ringrose-Voase, A. J. and Humphreys, G. S., editors, *Soil Micromorphology: study in management and genesis. Proc. IX Int. Work Meeting on Soil Micromorphology, Townsville, Australia*, pages 411–419. Developments in Soil Science 22, Elsevier, Amsterdam.

Minet, J. 2007. Influence de la dispersion du parcellaire sur la gestion du risque climatique au Fakara, Niger. Mémoire de Bio-Ingénieur. Faculté d'Ingénierie biologique, agronomique et environnementale. Université catholique de Louvain, Belgique. 97p + annexes.

Moeller, C., Pala, M., Manschadi, A. M., Meinke, H., and Sauerborn, J. 2007. Assessing the sustainability of wheat-based cropping systems using APSIM: model parameterisation and evaluation. *Australian Journal of Agricultural Research*, 58:75–86.

Monteith, J. L., Marshall, B., Saffell, R. A., Clarke, D., Gallagher, J. N., Gregory, P. J., Ong, C. K., Squire, G. R., and Terry, A. 1983. Environmental-Control of a Glasshouse Suite for Crop Physiology. *Journal of Experimental Botany*, 34:309–321.

Muchena, P. and Iglesias, A. 1995. Vulnerability of maize yields to climate change in different farming sectors in Zimbabwe. *Climate change and agriculture: analysis of potential international impacts, Published by American Society of Agronomy; ASA Special Publication, 59, Editors Rosenzweig C. and et al.*, pages 229–239.

Naab, J. B., Singh, P., Boote, K. J., Jones, J. W., and Marfo, K. O. 2004. Using the Cropgro-Peanut Model to Quantify Yield Gaps of Peanut in the Guinean Savanna Zone of Ghana. *Agronomy Journal*, 96:1231–1242.

Ong, C. K. 1983a. Response to Temperature in a Stand of Pearl-Millet (Pennisetum-Typhoides S and H). 1. Vegetative Development. *Journal of Experimental Botany*, 34:322–336.

Ong, C. K. 1983b. Response to Temperature in a Stand of Pearl-Millet (Pennisetum-Typhoides S and H). 4. Extension of Individual Leaves. *Journal of Experimental Botany*, 34:1731–1739.

Ong, C. K. 1984. Response to Temperature in a Stand of Pearl-Millet (Pennisetum-Typhoides S-and-H). 5. Development and Fate of Tillers. *Journal of Experimental Botany*, 35:83–90.

Ong, C. K. and Everard, A. 1979. Short-day induction of flowering in pearl millet (Pennisetum typhoides) and its effect on plant morphology. *Experimental agriculture*, 15:401–410.

Ozer, P., Erpicum, M., Demaree, G., and Vandiepenbeeck, M. 2003. The Sahelian Drought May Have Ended During the 1990s: Discussion of "Analysis of a Sahelian Annual Rainfall Index From 1896 to 2000: the Drought Continues". *Hydrological Sciences Journal-Journal Des Sciences Hydrologiques*, 48:489–492.

Palm, C. A., Myers, R. J. K., and Nandwa, S. M. 1997. Combined use of organic and inorganic nutrient sources for soil fertility maintenance and replenishment. In Buresh, R. and Sanchez, P., editors, *Replenishing Soil Fertility in Africa. SSSA Special Publication 51*. WI: Soil Science Society of America (SSSA), Madison.

Pandey, A. K., Prakash, V., Singh, R. D., and Gupta, H. S. 2001a. Contribution and Impact of Production Factors on Growth, Yield Attributes, Yield and Economics of Rainfed Wheat (Triticum Aestivum). *Indian Journal of Agronomy*, 46:674–681.

Pandey, R. K., Maranville, J. W., and Bako, Y. 2001b. Nitrogen fertilizer response and use efficiency for three cereal crops in niger. *Communications in Soil Science and Plant Analysis*, 32:1465–1482.

Payne, W. A. 1997. Managing Yield and Water Use of Pearl Millet in the Sahel. *Agronomy Journal*, 89:481–490.

Payne, W. A. 2000. Optimizing Crop Water Use in Sparse Stands of Pearl Millet. *Agronomy Journal*, 92:808–814.

Payne, W. A., Lascano, R. J., Hossner, L. R., Wendt, C. W., and Onken, A. B. 1991. Pearl-Millet Growth as Affected by Phosphorus and Water. *Agronomy Journal*, 83:942–948.

Payne, W. A., Drew, M. C., Hossner, L. R., Lascano, R. J., Onken, A. B., and Wendt, C. W. 1992. Soil-Phosphorus Availability and Pearl-Millet Water-Use Efficiency. *Crop Science*, 32:1010–1015.

Phillips, J. G., Cane, M. A., and Rosenzweig, C. 1998. ENSO, seasonal rainfall patterns and simulated maize yield variability in Zimbabwe. *Agricultural and Forest Meteorology*, 90:39–50.

Popov, G. F. 1984. Crop monitoring and forecasting. In *Agrometeorology of sorghum and millet in the semi-arid tropics. Proceedings of an international workshop 15-20 Nov 1982, A.P.502324,*, pages 307–316. ICRISAT, Patancheru, AP, India.

Powell, J. M., Fernandezrivera, S., and Hofs, S. 1994. Effects of Sheep Diet on Nutrient Cycling in Mixed Farming Systems of Semiarid West-Africa. *Agriculture Ecosystems & Environment*, 48:263–271.

Powell, J. M., Ikpe, F. N., Somda, Z. C., and Fernandez-Rivera, S. 1998. Urine Effects on Soil Chemical Properties and the Impact of Urine and Dung on Pearl Millet Yield. *Experimental Agriculture*, 34:259–276.

Probert, M. E. 2004. A capability in APSIM to model Phosphorus responses in crops. In Delve, R. J. and Probert, M. E., editors, *Modelling nutrient management in tropical cropping systems*, pages 92–100. Canberra, Australian Center for International Agricultural Research (ACIAR) No 114.

Probert, M. E., Dimes, J. P., Keating, B. A., Dalal, R. C., and Strong, W. M. 1998. Apsim's Water and Nitrogen Modules and Simulation of the Dynamics of Water and Nitrogen in Fallow Systems. *Agricultural Systems*, 56:1–28.

Reardon, T., Kelly, V., Crawford, E., Diagana, B., Dione, J., Savadogo, K., and Boughton, D. 1997. Promoting Sustainable Intensification and Productivity Growth in Sahel Agriculture After Macroeconomic Policy Reform. *Food Policy*, 22:317–327.

Rebafka, F. P., Bationo, A., and Marschner, H. 1993. Phosphorus seed coating increases P uptake, early growth and yield of pearl millet (Pennisetum glaucum (L.) R. Br.) grown on an acid sandy soil in Niger, West Africa. *Fertiliser Research*, 35:151–160.

Rebafka, F. P., Hebel, A., Bationo, A., Stahr, K., and Marschner, H. 1994. Short-Term and Long-Term Effects of Crop Residues and of Phosphorus Fertilization on Pearl-Millet Yield on an Acid Sandy Soil in Niger, West-Africa. *Field Crops Research*, 36:113–124.

Reddy, K. C. 1988. Stratégies alternatives pour la production de mil/niébé pendant l'hivernage. Fascicule No. 1. Institut National de Recherches Agronomiques du Niger (INRAN), BP 429, Niamey, Niger.

Reddy, K. C. and Visser, P. L. 1993. Late planting effects on early versus late pearl millet genotypes in Niger. *Experimental Agriculture*, 29:121–129.

Robertson, M. J., Sakala, W., Benson, T., and Shamudzarira, Z. 2005. Simulating response of maize to previous velvet bean (Mucuna pruriens) crop and Nitrogen fertilizer in Malawi. *Field Crops Research*, 91:91–105.

Rockstrom, J. 1999. On-Farm Green Water Estimates as a Tool for Increased Food Production in Water Scarce Regions. *Physics and Chemistry of the Earth Part B-Hydrology Oceans and Atmosphere*, 24:375–383.

Rockstrom, J. and De Rouw, A. 1997. Water, Nutrients and Slope Position in on-Farm Pearl Millet Cultivation in the Sahel. *Plant and Soil*, 195:311–327.

Samba, A. 1998. Les logiciels DHC de diagnostic hydrique des cultures. Prévision des rendements du mil en zones soudano-sahéliennes de l'Afrique de l'Ouest. *Cahiers d'études et de recherches francophones / Sécheresse*, 9:281–288.

Sangaré, M., Bationo, A., Hiernaux, P., Fernandez-Rivera, S., and Pandey, V. 2002. Effect of Type and Level of Roughage Offered to Sheep and Urine Addition on Compost Quality and Millet Growth and Production in the Sahel. *Nutrient Cycling in Agroecosystems*, 62:203–208.

Schlecht, E. and Buerkert, A. 2004. Organic Inputs and Farmers' Management Strategies in Millet Fields of Western Niger. *Geoderma*, 121:271–289.

Schlecht, E., Hiernaux, P., Achard, F., and Turner, M. D. 2004. Livestock Related Nutrient Budgets Within Village Territories in Western Niger. *Nutrient Cycling in Agroecosystems*, 68:199–211.

Schlecht, E., Buerkert, A., Tielkes, E., and Bationo, A. 2006. A Critical Analysis of Challenges and Opportunities for Soil Fertility Restoration in Sudano-Sahelian West Africa. *Nutrient Cycling in Agroecosystems*, 76:109–136.

Scott-Wendt, J., Chase, R. G., and Hossner, L. R. 1988a. Soil chemical variability in sandy Ustalfs in semi-arid Niger, West Africa. *Soil science*, 145:414–419.

Scott-Wendt, J., Hossner, L. R., and Chase, R. G. 1988b. Variability in Pearl millet (Pennisetum americanum) fields in semiarid west Africa. *Arid soil research and rehabilitation*, 2:49–58.

Shamudzarira, Z. and Robertson, M. J. 2002. Simulating response of maize to nitrogen fertilizer in semi-arid Zimbabwe. *Experimental Agriculture*, 38:79–96.

Shamudzarira, Z., Waddington, S., Robertson, M. J., Keating, B. A., Mushayi, P., Chiduza, C., and Grace, P. 2000. Simulating N fertilizer response in low-input farming systems. 1.

Fertiliser recovery and crop response. Risk management working paper. CIMMYT Series 00/05.

Shapiro, B. I. and Sanders, J. H. 1998. Fertilizer Use in Semiarid West Africa: Profitability and Supporting Policy. *Agricultural Systems*, 56:467–482.

Shaykewich, C. F. 1995. An Appraisal of Cereal Crop Phenology Modeling. *Canadian Journal of Plant Science*, 75:329–341.

Sinaj, S., Buerkert, A., El-Hajj, G., Bationo, A., Traoré, H., and Frossard, E. 2001. Effects of Fertility Management Strategies on Phosphorus Bioavailability in Four West African Soils. *Plant and Soil*, 233:71–83.

Sivakumar, M. V. K. 1988. Predicting rainy season potential from the onset of rains in southern sahelian and sudanian climatic zones of West Africa. *Agricultural and forest meteorology*, 42:295–305.

Sivakumar, M. V. K. 1989. Agroclimatic aspects of rainfed agriculture in the Sudano-sahelian zone. In Sivakumar, M. V. K., Wallace, J. S., Renard, C., and Giroux, C., editors, *Soil, crop, and water management systems for rainfed agriculture in the Sudano-Sahelian zone. Proceedings of an international workshop*. ICRISAT, Patancheru, AP, India.

Sivakumar, M. V. K. 1990. Exploiting Rainy Season Potential From the Onset of Rains in the Sahelian Zone of West-Africa. *Agricultural and Forest Meteorology*, 51:321–332.

Sivakumar, M. V. K. 1992. Empirical-Analysis of Dry Spells for Agricultural Applications in West Africa. *Journal of Climate*, 5:532–539.

Sivakumar, M. V. K. and Salaam, S. A. 1999. Effect of Year and Fertilizer on Water-Use Efficiency of Pearl Millet (Pennisetum Glaucum) in Niger. *Journal of Agricultural Science*, 132:139–148.

Sivakumar, M. V. K., Maidoukia, A., and Stern, R. D. 1993. Agroclimatology of West Africa: Niger. Information Bulletin no 5. Patancheru, A.P. 502 324, India: Internationational Crops Research Institute for the Semi-Arid Tropics, and Niamey: Direction de la météorologie nationale du Niger. 116p.

Ska, O. 2005. Les propriétés chimiques des sols de parcelles cultivées dans le Fakara (Niger). Mémoire de Bio-Ingénieur. Faculté d'Ingénierie biologique, agronomique et environnementale. Université catholique de Louvain, Belgique. 171p + annexes.

Smaling, E. M. A., Stoorvogel, J. J., and Windmeijer, P. N. 1993. Calculating Soil Nutrient Balances in Africa at Different Scales. 2. District Scale. *Fertilizer Research*, 35:237–250.

Squire, G. R. 1989a. Response to Temperature in a Stand of Pearl-Millet. 10. Partition of Assimilate. *Journal of Experimental Botany*, 40:1391–1398.

Squire, G. R. 1989b. Response to Temperature in a Stand of Pearl-Millet. 9. Expansion Processes. *Journal of Experimental Botany*, 40:1383–1389.

Squire, G. R., Marshall, B., Terry, A. C., and Monteith, J. L. 1984. Response to Temperature in a Stand of Pearl-Millet. 6. Light Interception and Dry-Matter Production. *Journal of Experimental Botany*, 35:599–610.

Sterk, G., Stein, A., and Stroosnijder, L. 2004. Wind Effects on Spatial Variability in Pearl Millet Yields in the Sahel. *Soil & Tillage Research*, 76:25–37.

Stockle, C. O., Donatelli, M., and Nelson, R. 2003. Cropsyst, a Cropping Systems Simulation Model. *European Journal of Agronomy*, 18:289–307.

Subbarao, G. V., Renard, C., Bationo, A., van Duivenbooden, N., and Bielders, C. 1999. Alternative technologies for the Sahelian crop production systems in west Africa. In Faroda, A. S., Joshi, N. L., Kathju, S., and Kar, A., editors, *Management of Arid Ecosystem*, pages 121–132. Arid Zone Research Association of India, and Scientific Publishers, Jodhpur.

Subbarao, G. V., Renard, C., Payne, W. A., and Bationo, A. 2000. Long-Term Effects of

Tillage, Phosphorus Fertilization and Crop Rotation on Pearl Millet-Cowpea Productivity in the West-African Sahel. *Experimental Agriculture*, 36:243–264.

Sultan, B., Baron, C., Dingkuhn, M., Sarr, B., and Janicot, S. 2005a. Agricultural Impacts of Large-Scale Variability of the West African Monsoon. *Agricultural and Forest Meteorology*, 128:93–110.

Sultan, B., Baron, C., Dingkuhn, M., Sarr, B., and Janicot, S. 2005b. La variabilité climatique en Afrique de l'Ouest aux échelles saisonnières et intra-saisonnière. II: Applications à la sensibilité des rendements agricoles au Sahel. *Cahiers d'études et de recherches francophones / Sécheresse.*, 16:23–33.

Tabo, R., Bationo, A., Gérard, B., Ndjeunga, J., Marchal, D., Amadou, B., Annou, G., Sogodogo, D., Sibiry, J. B., Hassane, O., Diallo, M., and Koala, S. 2007. Improving cereal productivity and farmers' income using a strategic application of fertilizers in West Africa. In Bationo, A., editor, *Advances in Integrated Soil Fertility Management in Sub-Saharan Africa: Challenges and Opportunities*, pages 201–208. Springer Netherlands., Netherlands.

Thompson, L. M. 1986. Climate change, weather variability, and corn production. *Agronomy Journal*, 78:649.

Thorburn, P. J., Probert, M. E., and Robertson, F. A. 2001. Modelling Decomposition of Sugar Cane Surface Residues With Apsim-Residue. *Field Crops Research*, 70:223–232.

Thornton, P. K., Bowen, W. T., Ravelo, A. C., Wilkens, P. W., Farmer, G., Brock, J., and Brink, J. E. 1997. Estimating millet production for famine early warning: an application of crop simulation modelling using satellite and ground-based data in Burkina Faso. *Agricultural and Forest Meteorology*, 83:95–112.

Tittonell, P., Zingore, S., Wijk, M. T. V., Corbeels, M., and Giller, K. E. 2007. Nutrient Use Efficiencies and Crop Responses to N, P and Manure Applications in Zimbabwean Soils: Exploring Management Strategies Across Soil Fertility Gradients. *Field Crops Research*, 100:348–368.

Ukkerman, R. and Hama, B. 1995. Evaluation des systemes de cultures. PRIVAT (Projet participatif de Renforcement des Instititions Villageoises pour le développement de l'Agriculture du Département de Tahoua. BP 86, Konni, Niger.

Valentin, C. 1991. Surface crusting in two alluvial soils of northen Niger. *Geoderma*, 48:201–222.

Van Oosterom, E. J., Carberry, P. S., Hargreaves, J. N. G., and O'leary, G. J. 2001a. Simulating Growth, Development, and Yield of Tillering Pearl Millet II. Simulation of Canopy Development. *Field Crops Research*, 72:67–91.

Van Oosterom, E. J., Carberry, P. S., and O'leary, G. J. 2001b. Simulating Growth, Development, and Yield of Tillering Pearl Millet I. Leaf Area Profiles on Main Shoots and Tillers. *Field Crops Research*, 72:51–66.

Van Oosterom, E. J., O'leary, G. J., Carberry, P. S., and Craufurd, P. Q. 2002. Simulating Growth, Development, and Yield of Tillering Pearl Millet. III. Biomass Accumulation and Partitioning. *Field Crops Research*, 79:85–106.

van Rossum, G. 2006. Python Reference Manual, Release 2.5.

Van Vyve, N. 2006. Caractérisation de la variabilité spatio-temporelle de la pluie au Fakara, Niger. Mémoire de Bio-Ingénieur. Faculté d'Ingénierie biologique, agronomique et environnementale. Université catholique de Louvain, Belgique. 68p + Annexes.

Vanlauwe, B. and Giller, K. E. 2006. Popular myths around soil fertility management in sub-Saharan Africa: Nutrient Management in Tropical Agroecosystems. *Agriculture, Ecosystems & Environment*, 116:34–46.

Voortman, R. L. and Brouwer, J. 2003. An Empirical Analysis of the Simultaneous Effects of Nitrogen, Phosphorus and Potassium in Millet Production on Spatially Variable Fields in South-west Niger. *Nutrient Cycling in Agroecosystems*, 66:143–164.

Voortman, R. L., Brouwer, J., and Albersen, P. J. 2004. Characterization of Spatial Soil Variability and Its Effect on Millet Yield on Sudano-Sahelian Coversands in Sw Niger. *Geoderma*, 121:65–82.

Wafula, B. M. 1995. Applications of crop simulation in agricultural extension and research in Kenya. *Agricultural Systems*, 49:399–412.

Wang, X. B., Cai, D. X., Hoogmoed, W. B., Perdok, U. D., and Oenema, O. 2007. Crop Residue, Manure and Fertilizer in Dryland Maize Under Reduced Tillage in Northern China: I Grain Yields and Nutrient Use Efficiencies. *Nutrient Cycling in Agroecosystems*, 79:1–16.

Wendt, J. W., Berrada, A., Gaoh, M. G., and Schulze, D. G. 1993. Phosphorus Sorption Characteristics of Productive and Unproductive Niger Soils. *Soil Science Society of America Journal*, 57:766–773.

West, L. T., Wilding, L. P., Landeck, J. K., and F.G., C. 1984. Soil Survey of the ICRISAT Sahelian Center, Niger, West Africa.

Weynants, M. 2005. Caractérisation des propriétés hydrodynamiques et étude de la possibilité d'agrégation de trois types de sols au Fakara, Niger. Mémoire de Bio-Ingénieur. Faculté d'Ingénierie biologique, agronomique et environnementale. Université catholique de Louvain, Belgique. 100p + annexes.

Williams, T. O. 1999. Factors influencing manure application by farmers in semi-arid west Africa. *Nutrient cycling in agroecosystems*, 55:15–22.

Winkel, T., Renno, J., and Payne, W. 1997. Effect of the timing of water deficit on growth, phenology and yield of pearl millet (Pennisetum glaucum (L.) R. Br.) grown in Sahelian conditions. *Journal of Experimental Botany*, 48:1001–1009.

Yamoah, C. F., Bationo, A., Shapiro, B., and Koala, S. 2002. Trend and Stability Analyses of Millet Yields Treated With Fertilizer and Crop Residues in the Sahel. *Field Crops Research*, 75:53–62.

Yan, W. and Hunt, L. A. 1999. An Equation for Modelling the Temperature Response of Plants using only the Cardinal Temperatures. *Annals of Botany*, 84:607–614.

Yan, W. and Wallace, D. H. 1998. Simulation and Prediction of Plant Phenology for Five Crops Based on Photoperiod x Temperature Interaction. *Annals of Botany*, 81:705–716.

Zaongo, C. G. L., Wendt, C. W., Lascano, R. J., and Juo, A. S. R. 1997. Interactions of Water, Mulch and Nitrogen on Sorghum in Niger. *Plant and Soil*, 197:119–126.

APPENDIX: APSIM Pearl Millet Module Description*

Millet module scope

The millet module simulates the growth and development of a pearl millet crop in a daily time step. The module is specifically designed to deal with the tillering nature of the millet crop. Each axis of the crop is considered to be a different crop, and the competition for resources between the axes is simulated analogous to an intercrop. Pearl millet growth responds to climate (temperature, rainfall, radiation), soil water supply (from soilwat2 module), and soil nitrogen (from soiln2 module)and returns information on soil water and soil nitrogen to the soilwat2 and soiln2 modules on a daily basis for resets of these systems. Information on crop cover is also provided to the soilwat2 module to calculate evaporation rates and runoff. Pearl millet stover and root residues are passed from millet to the residue2 and soiln2 module respectively at harvest of the millet crop.

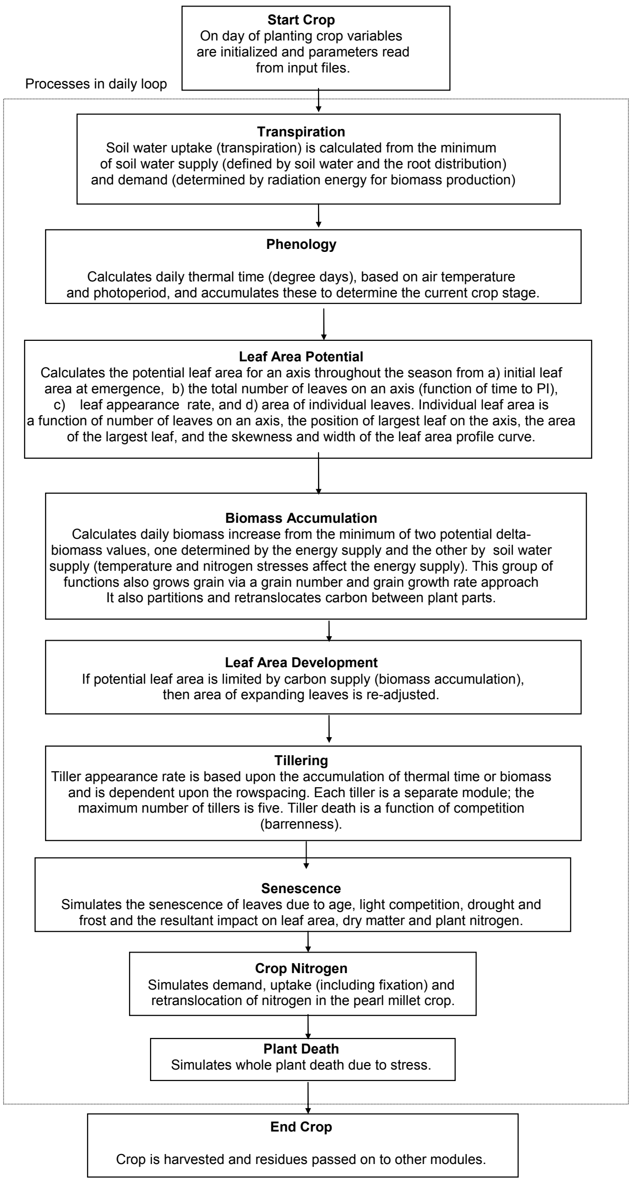
A list of the module outputs is provided in the 'Millet module outputs' section towards the end of the document. The module simulates biomass (above and below ground), grain yield, leaf area development, N-contenets for individual plant parts, and yield components, all on a daily time step for individual axes.

Millet module history

The module was adapted from CERES-MAIZE, and is currently very similar to the Crop template in APSIM. The major difference with any other module in APSIM is that it simulates the growth and development of individual tillers, by considering the entire crop as an intercrop of the different axes. The module has been parameterised based on data from experiments conducted at the ICRISAT research station at Patancheru, India, under optimum growing conditions, covering a range of plant den-

*Reproduced from: APSIM 3.6 user manual (Working group: Peter Carberry, Erik van Oosterom, John Hargreaves, Garry O'Leary.)

sities and genotypes (Van Oosterom *et al.*, 2001a,b). The module adequately predicts biomass, grain yield, and LAI across a range of plant densities, photoperiods, and genotypes. However, all the validation data sets were obtained from experiments conducted at Patancheru. We are currently (December 2000) in the process of collating data sets form other parts of the world to extend the range in maximum LAI, biomass and grain yield in the validation data sets.



Millet module components

Phenology

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 sowing to germination which is driven by soil moisture. Each day the phenology routines calculate today's thermal time (in degree days) from 3-hourly air temperatures interpolated from the daily maximum and minimum temperatures. 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. The eight 3-hourly estimates are averaged to obtain the daily value of thermal time. These daily values are summed into a thermal time sum which is used to determine the duration of each phase. Between the stage of emergence and flag leaf, the calculated daily thermal time is reduced by water or nitrogen stresses, 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 values input in the millet.par file. Sowing to germination is dependent on soil water levels; the phase germination_to_emergence includes an effect of sowing depth on the thermal time target; and the phase between end_of_juvenile and floral initiation is determined by a cultivar's photoperiod (daylength) sensitivity - note that pearl millet is a short-day plant. The crop phases from germination to maturity and their thermal time duration for cv. BJ104 (main shoot) are listed below.

tt(germ to emerg) = 10.7 °Cd+ (sowing depth * 1.17) °Cdays (sowing depth in mm)
tt(emerg_end_juvenile) = 239 °Cdays
tt(end_juvenile_floral-intiation) = 112 * active photoperiod °Cdays (base photoperiod 12.9 h)
tt(emergence_to_flag leaf) = leaf number * 36.4 °Cdays
tt(flagleaf_to_flowering) = 66.1 °Cdays
tt(flowering_to_start-grainfill) = 80 °Cdays
tt(flowering_to_maturity)= 457 °Cdays
tt(maturity to harvest-ripe) = 1 °Cdays

The period between flowering and maturity is divided into three phases. The first phase, which covers the period from flowering to the start of grain filling, is genotype-specific (see above). The third phase is the period from end of grain filing until maturity, and is set to 5% of the total period. The actual grain growth phase is finally calculated as the difference between the duration of the total period and the other two phases.

The final leaf number on the main shoot is calculated as the sum of the number of leaves present in the seed (four) and the product of the time from germination to end juvenile and the leaf initiation rate (27.2 °Cd/leaf). For tillers, however, leaf number is estimated from the leaf number on the main shoot, as detailed data on time from initiation to end juvenile are not available for tillers. In general, tiller 1 (which appears from axil of leaf 3) has 4 leaves less than the main shoot.

Biomass accumulation (Photosynthesis)

Each day two estimates of the daily biomass production are calculated, one limited by available water for transpiration (Eqn. 1), and the other limited by radiant energy (Eqn. 2). The minimum of these two estimates is the actual biomass production for the day

dlt_dm_transp = sw_supply_sum * millet_transp_eff (Eqn. 1)

In this equation, sw_supply_sum is the total water supply over all soil layers where roots are present. Transpiration efficiency (TE) is derived from the TE coefficient and the vapour pressure deficit (vpd), which in turn is estimated from daily temperatures.

dlt_drymatter_potential = rue *radiation_interception (Eqn. 2)

Radiation use efficiency (RUE) is calculated as:

rue = rue(current_phase) * millet_rue_reduction (Eqn. 3)

rue(current_phase) is 1.9 before anthesis and 1.4 thereafter. The rue reduction is a factor that incorporates temperature and nitrogen stresses. Radiation interception is a function light interception by the crop and daily radiation.

Biomass partitioning

Daily biomass production is partitioned to different plant parts; the ratios depend on the crop stage.

Roots are grown daily in a fixed proportion to the tops production. This proportion (root shoot ratio) is specified for each growth stage and declines from 1.0 beforel panicle initiation to 0.0 from the start of grain filling onwards:

eme juv PI flag flow
1 1 0.33 0.33 0.087

Between emergence and panicle initiation, 67% of the biomass is allocated to the leaves, and 33% to the stems, which include the leaf sheath.

Between panicle initiation and flag leaf, stem elongation and flower development start. Therefore, partitioning to leaves declines linearly from 67% at panicle initiation to 0% at flag leaf. If the amount of carbon partitioned to leaves is more than is required for the calculated increase in leaf area (the leaves have a maximum thickness) then the residual is partitioned to flowers and stems:

dlt_dm_green(flower) = (dlt_dm_axis - dlt_dm_green(leaf)) * frac_stem2flower (Eqn. 4)

where frac_stem2flower is set to 0.19.

dlt_dm_green(stem) = dlt_dm_axis - (dlt_dm_green(leaf) + dlt_dm_green(flower)) (Eqn. 5)

If the carbon partitioned to leaves is insufficient to grow the potential increase in leaf area, leaf area increase is reduced (see leaf area development section).

Between flag leaf and start of grain filling, only stems and flowers grow. It is assumed that 19% of the produced dry matter is allocated to flowers and 81% to stems.

Between the start of grain filling and maturity, biomass is partitioned to grains, whereas stems will continue growing if they can. Grain demand for carbohydrate (biomass) is driven by grain number and grain growth rate. Grain number is a function of the rate of dry matter accumulation between the flag leaf stage and the start of grain filling. Grain growth rate is limited by temperature and drought stress. It is genotype specific and thus accounts for genotypic differences in grain mass and harvest index.

Biomass retranslocation

If the grain demand for carbohydrate cannot be met through partitioning of daily biomass production, it is retranslocated from other plant parts to meet (if possible) this grain demand. The carbohydrate in stem and leaf that is available for transfer, is calculated from the difference between potential and minimum weight for stem and leaf. Dry matter is first translocated from the stems; if not all the demand can be met, the remaining dry matter will be translocated from the leaves.

Leaf development

Potential leaf area Potential crop leaf area is simulated from the area of individual leaves. Leaf area might be reduced if insufficient dry matter is produced in the subsequent routine on biomass accumulation. First, leaf area is initialised at emergence and the final leaf number (on an axis) is calculated. Final leaf number is calculated at panicle initiation, but an approximate number is set at germination to allow other calculations to proceed until the correct number is known. The number of fully expanded leaves throughout the season is calculated from the appearance rate of fully expanded leaves, which is set at 36.4 °Cdays. An adjustment in leaf number is made to account for the area of the expanding leaves. Individual leaf area is calculated from a cubic function:

$Y = Y0 \exp(a(X-X0)^2 + b(X-X0)^3)$ (Eqn. 6)

where Y = mature leaf area of individual leaf, Y0 = mature area of largest leaf, X0 = position of largest leaf, a = empirical constant determining the breadth of the leaf area profile curve, b = empirical constant determining the skewness of the leaf area profile. The four coefficients (X0, Y0, a, b) are functions of final leaf number. Parameter Y0 is genotype-, density-, and axis-specific, whereas the other parameters are mainly axis-specific. Because of sensitivity of cell expansion to water deficits, leaf area development is reduced under drought stress.

Actual leaf area The actual LAI is less than the potential if there is not sufficient biomass partitioned to leaves on that day. The maximum specific leaf area (sla_max) defines the maximum leaf area (m^2) that can be expanded per gram of leaf biomass. The maximum SLA is set to 650 cm^2/g if LAI (for an individual axis) < 2, and declines linearly to 450 cm^2/g if LAI (for an individual axis) drops from 2.0 to 5.0.

Leaf senescence The number of senesced leaves on an axis is a linear function of time, although the slope of the function is higher before flag leaf stage (0.0167 leaves/°Cd) than after (0.0120 leaves/°Cd). The slopes are independent of genotype and axis, but the onset of senescence is later in tillers than in the main shoot.

The senesced leaf area (as a function of age) for each axis is calculated from the senesced leaf number. In addition, senesced leaf area is calculated as a function oflight competition, water stress, and temperature stress. The maximum of these four is used as the actual leaf area that has sensesced during that particular day.

Tillering

Tiller appearance Tillering starts at 150 oCd, at a rate of 34 oCd per tiller. Tillers may appear until flag leaf stage, but the maximum tiller number is set to 5. A switch gives the option to make tillering a function of thermal units or dry matter. At the moment, it is driven by thermal units. The rate of tiller appearance is not dependent on genotype, as genotypic differences in tillering are a result of differences in tiller survival, rather than tiller appearance.

Tiller death Tillers that capture insufficient resources to produce a panicle are killed at the start of grain filling. The mechanism employed is barrenness, a condition where the tiller will not set any grain, because the average growth rate between flag leaf and start grain filling is below a critical value, which is currently set at 0.10 g/plant/day.

Regrowth

There are no regrowth routines in millet.

Water uptake

To determine the amount of water supply to the crop on any day, first the total available water above the lower limit for all soil layers with roots is summed (Eqn. 7). If roots are only partially through a layer, available soil water is scaled to that portion that contains roots. The kl constant (value differs for each soil layer) is then used to limit the amount of water available on any day (Eqn. 8). The kl factor is empirically derived, incorporating both plant and soil factors which limit rate of water uptake. Figure 1 shows how kl limits water uptake as soil water approaches the lower limit.
do layer = 1, deepest_layer (do loop to calculate available water for all layers)
sw_avail = sw(layer) - ll (layer) (Eqn. 7)
sw_supply(layer) = sw_avail * kl (layer) (Eqn. 8)

Soil water demand is calculated as in the 'biomass accumulation' section above where potentail biomass production is a function of light interception and rue (Eqn. 3). This potential biomass production is converted to water demand using transpiration efficiency.

sw_demand = dlt_dm_pot / millet_transp_eff (Eqn. 9)

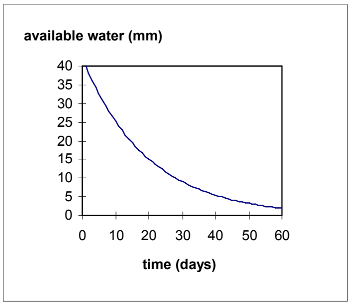


Figure 1. Relationship between water availability and rate of water extraction as determined by the kl value.

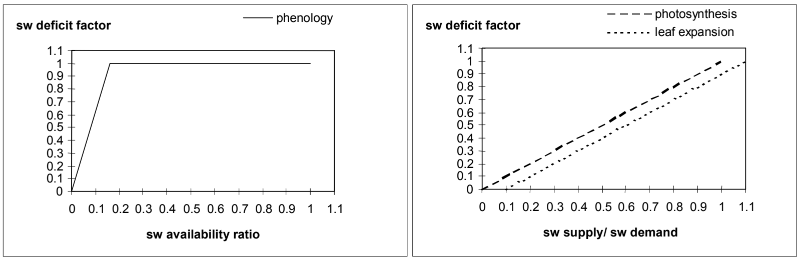


Figure 2. a. Soil water deficit factor for phenology as a function of the soil water availability ratio. b) soil water deficit factors for photosynthesis and leaf expansion as a function of soil water supply/demand ratio.

Water uptake is the minimum of the supply and demand.

Water deficits affecting plant growth

Soil water deficit factors are calculated to simulate the effects of water deficits on different plant growth processes. Three water deficit factors are calculated which correspond to three plant processes each having different sensitivity to water stress: photosynthesis (photo), phenology (pheno), and leaf-expansion (expansion).

The effect of water deficits on phenology is a function of the water availability ratio, which is calculated by dividing the available soil water (soil water (sw) - lower limit (ll)) by the potential available soil water (drained upper limit (dul) - lower limit (ll)) (Fig 2a). A factor of 0 is complete stress and 1 no stress. For photosynthesis and leaf expansion, the effect of water deficits is a function of the soil water demand ratio, which is calculated as the soil water supply divided by the demand (Fig. 2b). The relationships in Fig. 2b reflect the greater sensitivity of leaf expansion (as compared to photosynthesis) to drought.

Nitrogen uptake and retranslocation

In order to calculate nitrogen demand today, first potential biomass production is recalculated unlimited by water, nitrogen or temperature i.e. as a function of rue and radiation-interception (Eqn. 3). This dry matter (biomass) is then partition into plant parts according to their current relative weights. The millet module has a defined minimum, critical and maximum N concentration for each plant part. Demand for nitrogen in each part attempts to maintain nitrogen at the critical (non stressed) level. Nitrogen demand on any day is the sum of the demands from the pre-existing biomass of each part required to reach critical N content, plus the N required to maintain critical N concentrations in today's potentially assimilated biomass.

A nitrogen uptake maximum is defined as the nitrogen uptake required to bring all plant part N contents to the maximum allowable concentration.

Nitrogen supply is the sum of nitrogen available via mass flow (Eqn. 10) and by diffusion (Eqn. 11).
no3_massflow (layer) = no3_conc * delta_sw (layer) (Eqn. 10)
no3_diffusion (layer) = no3_conc * sw_avail_frac (Eqn. 11)

where sw_avail_frac is ratio of extractable soil-water over total soil-water. The layer values are summed to root depth.

If nitrogen demand cannot be satisfied by mass flow then it is supplied by diffusion. Uptake of N above the critical concentration can only occur through mass flow. Excess N can be stored in plant parts as concentration above the critical N-concentration but below the maximum concentration.

Nitrogen available for uptake is distributed to plant parts in proportion to their individual demands.

Nitrogen for grain is retranslocated from other plant parts and is thus not directly taken up from the soil or atmosphere to meet grain demand. Nitrogen is available for retranslocation from all parts except grain and roots; all other plant parts will translocate nitrogen until they reach their defined minimum N concentration. Grain nitrogen demand is again driven by critical N content but this demand is lowered if the plant is under N stress. Grain N demand is also affected by temperature and water stress using Eqns. 12 and 13 below:
N_grain_temp_fac = 0.69 + 0.0125 * aver_temp (Eqn. 12)
N_grain_sw_fac = 1.125 - 0.125 * millet_swdef (expansion) (Eqn. 13)

The greatest of these two factors is multiplied by the previously calculated N demand i.e. if temperature is high or drought occurs, the N demand will be increased above the level required to reach the critical N concentration.

N fixation

No N fixation is assumed to occur (N fixation rate = 0.0).

Nitrogen deficits affecting plant growth

N availability factors (0-1) are calculated for the following processed: 1) grain N potential, 2) photosynthesis, 3) leaf senescence, grain N concentration, and cell expansion, 4) grain number. The N-concentration ratio which is calculated for the stover (stem + leaf) in Eqn 14 is used as a measure of N stress:
N_conc_ratio = (N_conc_stover - N_conc_stover_min) /
(N_conc_stover_crit - N_conc_stover_min) (Eqn. 14)

Different constants are used to convert this ratio to a deficit factor for each of the processes:

N_def = N_fact_(process) * N_conc_ratio (Eqn. 15)

where N_factor equals 1.25 (photosynthesis), 1.0 (grain concentration), 10.0 (phenology). As lower values of N_deficiency indicate more stress, phenology is least sensitive to nitrogen deficiency and grain N the most.

Root growth and distribution

Root depth is initialised at 110 mm. Between emergence and grain filling, the increase in root depth is a daily rate (20 mm/day) multiplied a soil water availability factor. Root depth is constrained by the soil profile depth.

Growth of root biomass is unrelated to depth and is as described in the 'biomass partitioning' section above.

Roots are not senesced during the life of the crop, but are incorporated in the soiln2 module at harvest and distributed as fresh organic matter in the profile according to an exponential relationship of depth and root biomass.

Temperature stress

There are no generic temperature factors, as for water and nitrogen stress, but as discussed in sections above temperature does influence grain N content, rate of senescence and radiation use efficiency (rue).

Plant death

All or some of the plants can be killed due to a variety of stresses;

If the crop hasn't germinated within 40 days of sowing, due to lack of germinating moisture, all plants are killed.

If the crop does not emerge with 150 oCdays of germination, because it was sown too deep, then all plants are killed.

If crop is past floral initiation and LAI = 0, then all plants are killed due to total senescence.

If the cumulative phenological water stress factors exceed 99, all plants are killed due to water stress prolonging phenology.

In addition, a fraction of the total number of plants can die due to:

1. high soil surface temperatures immediately following emergence.
2. drought stress, if a critical leaf number (set to 10) has not yet been reached.
3. barrenness at the start of grain filling.

Detachment

The detachment routines in millet are disabled in the current code.

Millet module parameterisation

Crop lower limit and kl values are need for each soil layer
extraction [icrisat_alf1.millet.parameters]
ll = 0.146 0.207 0.244 0.236 0.218 0.173 0.173 (mm/mm) ! millet lower limit
kl = 0.120 0.120 0.120 0.100 0.060 0.055 0.030 () ! rate of soil water extraction
extraction [icrisat_alf2.millet.parameters]
ll = 0.066 0.090 0.117 0.123 0.129 0.137 0.148 (mm/mm) ! lower limit
extraction [jodhpur_aridisol.millet.parameters]
ll = 0.040 0.043 0.043 0.043 0.040 0.040 0.040 (mm/mm) ! millet lower limit
kl values here are same as for icrisat_alf1. Needs to be changed for sandy soil texture of soil at Jodphur.
Phenology parameters needed for each cultivar:

[default.millet.bj104]
tt_emerg_to_endjuv = 239.4 (°Cd) ! TT from emergence to end of juvenile phase
est_days_emerg_to_init = 17 (d) ! estimated days from emergence to floral init.
pp_endjuv_to_init = 112.4 (°Cd/h) ! photoperiod sensitivity
tt_flower_to_maturity = 457.0 (°Cd) ! TT from flowering to maturity
tt_flag_to_flower = 66.1 (°Cd) ! TT from flag leaf to flowering
tt_flower_to_start_grain = 80.0 (°Cd) ! TT from flowering to start grain fill
tt_maturity_to_ripe = 1 (°Cd) ! TT from maturity to harvest ripe

Leaf area parameters needed for each cultivar:
y0_const = -12390.0 () ! intercept with y-axis of regression of the area of the largest leaf on
total leaf number
y0_slope = 1710.0 () ! slope of regression of the area of the largest leaf on total leaf number

Grain yield parameters needed for each cultivar:
hi_incr = 0.0 (1/day) ! rate of HI increase (optional)
hi_max_pot = 0.55 () ! maximum harvest index
head_grain_no_max = 3300.0 (grain/head) ! potential grains per head
grain_gth_rate = 0.61 (mg/grain/d) ! potential grain growth rate

All the above parameters are genotype specific, whereas tt_emerg_to_endjuv , y0_const, and y0_slope are also axis dependent.

Module dependencies

The minimum module configuration required to run millet in APSIM is the inclusion of the report, input, manager, soilwat2, soiln2, canopy, residue2, and millet modules. Operations are desirable in the case of validation runs to input observed data on crop management.

Within the manager file, the following syntax is used for the millet crop:

```
if (day = 171 and year = 1995) then
millet sow plants = 6.7, sowing_depth = 30, cultivar = wrajpop
crop_in = 1
endif
```

```
if (millet.stage_name = 'initiate' or millet.stage_name = 'emergence') then
tiller0_finished = 1
endif
if (millet1.stage_name = 'initiate' or millet1.stage_name = 'emergence') then
tiller1_finished = 1
endif
if (millet2.stage_name = 'initiate' or millet2.stage_name = 'emergence') then
tiller2_finished = 1
endif
if (millet3.stage_name = 'initiate' or millet3.stage_name = 'emergence') then
tiller3_finished = 1
endif
if (millet4.stage_name = 'initiate' or millet4.stage_name = 'emergence') then
tiller4_finished = 1
endif
if (millet5.stage_name = 'initiate' or millet5.stage_name = 'emergence') then
tiller5_finished = 1
endif
```

```
if (millet.stage_name = 'harvest_ripe' and millet.plant_status = 'alive') or
(millet.stage_name = 'end_crop' and millet.plant_status = 'dead') or
(tiller0_finished = 1 and millet.plant_status = 'out') then
```

```
millet harvest
millet kill_crop
millet end_crop
residue2 tillage_type = burn
tiller0_finished = 2
endif
```

[This is repeated for each tiller]

```
if (tiller0_finished = 2 and tiller1_finished = 2 and tiller2_finished = 2) and
(tiller3_finished = 2 and tiller4_finished = 2 and tiller5_finished = 2) then
crop_in = 0
tiller0_finished = 0
tiller1_finished = 0
tiller2_finished = 0
tiller3_finished = 0
```

```
tiller4_finished = 0
tiller5_finished = 0
endif
```

Module output

Millet module validation

The millet module was developed validated on a limited set of data collated mainly from on-station experiments at ICRISAT research station at Patancheru, India, and the CAZRI research station at Jodhpur, India. The validation data sets were largely independent of the development data set (van Oosterom et al., 2001b).

For most of the recent experiments (1995 onwards), soil chemical and physical characteristics are available. For most of the older data sets, however, this was not the case, and experiments were simulated assuming a fixed amount of water or nutrients being available in the soil. Since most of these experiments were supposedly non-limiting in water and nutrients, and since in most experiments received abundant rainfall and fertilizer, this should not have been a major problem.

In general, the model adequately captured the effects of density (Fig. 3), daylength (Fig. 4), genotype (Fig. 5) and N-supply (Fig. 6) on biomass accumulation, grain yield, and LAI. The results of Fig. 6 are particularly encouraging; whereas as most of the model development work was carried out at Patancheru (alfisols), in de absence of nitrogen and water stress, Fig. 6 shows an adequate simulation of the effects of N-stress at Jodhpur (sandy soils)

Millet module issues

Biomass partitioning

Panicle initiation is used as the trigger for the onset of stem elongation. In reality, however, the onset of stem elongation is not related to panicle initiation; the occurrence of panicle initiation is more sensitive to variation in daylength than the onset of stem elongation. Onset of stem elongation can therefore better be expressed relative to anthesis. Work on this issue is currently (December 2000) ongoing to better pinpoint the trigger for the onset of stem elongation.

Tiller death

Non-productive tillers cease producing leaves during stem elongation, but the size of the leaves that are prodcued is very similar to the leaf size of productive tillers. Hence, the low leaf area of non-productive tillers is a result of a reduction in leaf number, rather than leaf size. In the module, non-productive tillers die at anthesis due to barreness. They thus produce the same number of leaves as productive tillers, and

Table 1. APSIM millet module output

Variable Name	Units	Description
plant_status		status of crop
stage		current phenological stage
stage_code		
stage_name		
crop_type		
leaf_no		number of fully expanded leaves
leaf_no_dead		no of dead leaves
leaf_area (max_leaf = 1000)	mm^2	leaf area of each leaf
height	mm	canopy height
root_depth	mm	depth of roots
plants	plants/m^2	plant density
grain_no	grains/plant	grain number
grain_size	g	individual grain wt
cover_green	0-1	fraction of radiation reaching the canopy that is intercepted by the green
leaves of the canopy		
cover_tot	0-1	total crop cover fraction
lai_sum		leaf area index of all leaf material live + dead
tlai		tot lai
slai		area of leaf that senesces from plant
lai	m^2/m^2	live plant green lai
tlai_dead	m^2/m^2	total lai of dead plants
root_wt	g/m^2	root biomass
leaf_wt	g/m^2	leaf biomass
stem_wt	g/m^2	stem biomass
grain_wt	g/m^2	grain biomass
dm_green (max_part = 6)	g/m^2	live plant dry weight (biomass)
dm_senesced (max_part = 6)	g/m^2	senesced plant dry wt
dm_dead (max_part = 6)	g/m^2	dry wt of dead plants
yield	kg/ha	grain yield dry wt
biomass	kg/ha	total above-ground biomass
dlt_dm	g/m^2	the daily biomass production
dlt_dm_green (max_part = 6)	g/m^2	plant biomass growth
n_green (max_part = 6)	g/m^2	plant nitrogen content
n_senesced (max_part = 6)	g/m^2	plant n content of senesced plant
n_dead (max_part = 6)	g/m^2	plant n content of dead plants
dlt_n_green (max_part = 6)	g/m^2	actual n uptake into plant
dlt_n_retrans (max_part = 6)	g/m^2	nitrogen retranslocated out from parts to grain
dlt_n_detached (max_part = 6)	g/m^2	actual n loss with detached plant
dlt_n_dead_detached (max_part = 6)	g/m^2	actual n loss with detached dead plant
swdef_pheno		water deficit factor for phenology
swdef_photo		water deficit factor fo photosynthesis
swdef_expan		water deficit factor for leaf expansion
ep (num_layers)	mm	water uptake in each layer
cep	mm	cumulative water uptake
sw_demand	mm	total crop demand for water
sw_supply	mm	total supply over profile
esw_layr (num_layers)	mm	plant extractable soil water
n_conc_stover	%	sum of tops actual n concentration
n_conc_crit	%	sum of tops critical n concentration
n_grain_pcnt	%	grain n concentration percent
n_uptake_grain	kg/ha	n uptake by grain
n_uptake	kg/ha	cumulative total n uptake by plant
n_uptake_stover	kg/ha	n uptake by stover
no3_tot	g/m^2	total no3 in the root profile
n_demand	g/m^2	sum n demand for plant parts
n_supply	g/m^2	n supply for grain
n_supply_soil	g/m^2	n supply from soil
nfact_photo		N deficit factor for photosynthesis
nfact_grain		N deficit factor for grain N content

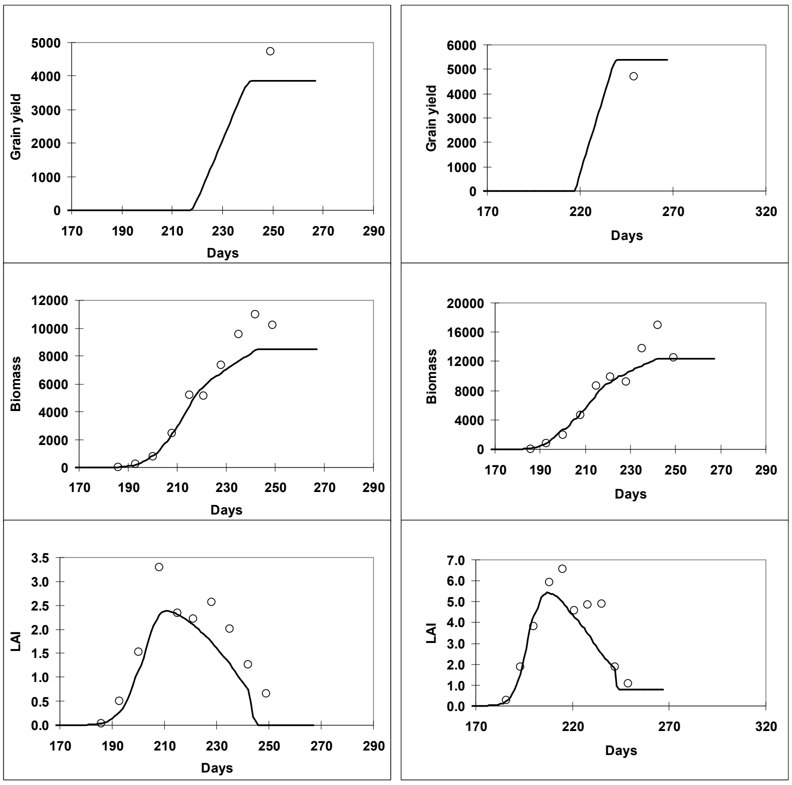


Figure 3. Simulation of grain yield, biomass, and LAI for BJ 104, grown at Patancheru in 1982 at densities of 4 (left) and 29 (right) plants /m^2.

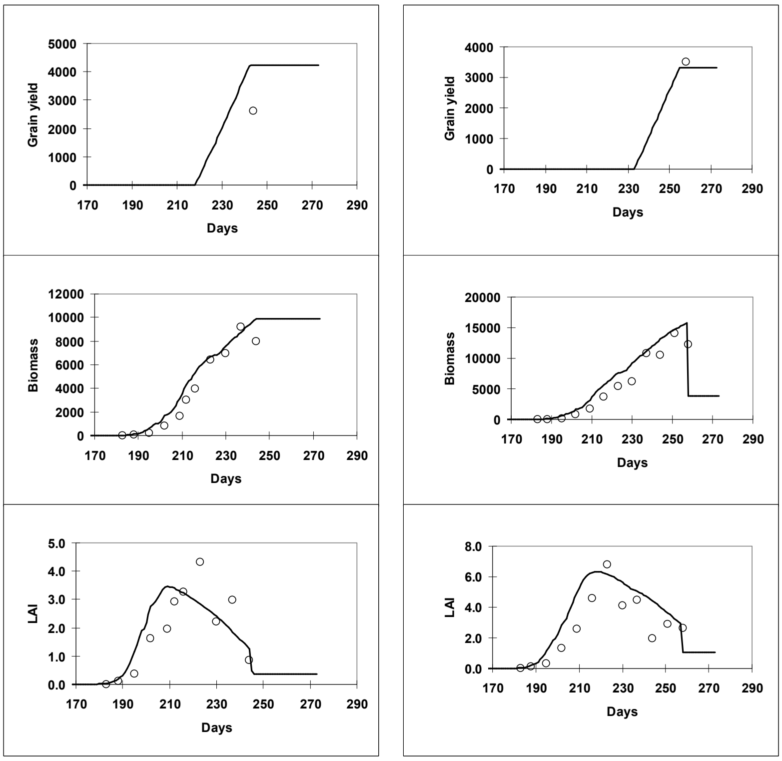


Figure 4. Simulation of grain yield, biomass, and LAI for BJ 104, grown at Patancheru in 1986 under normal daylength of 14 h (left) and extended daylength of 15.5 h (right).

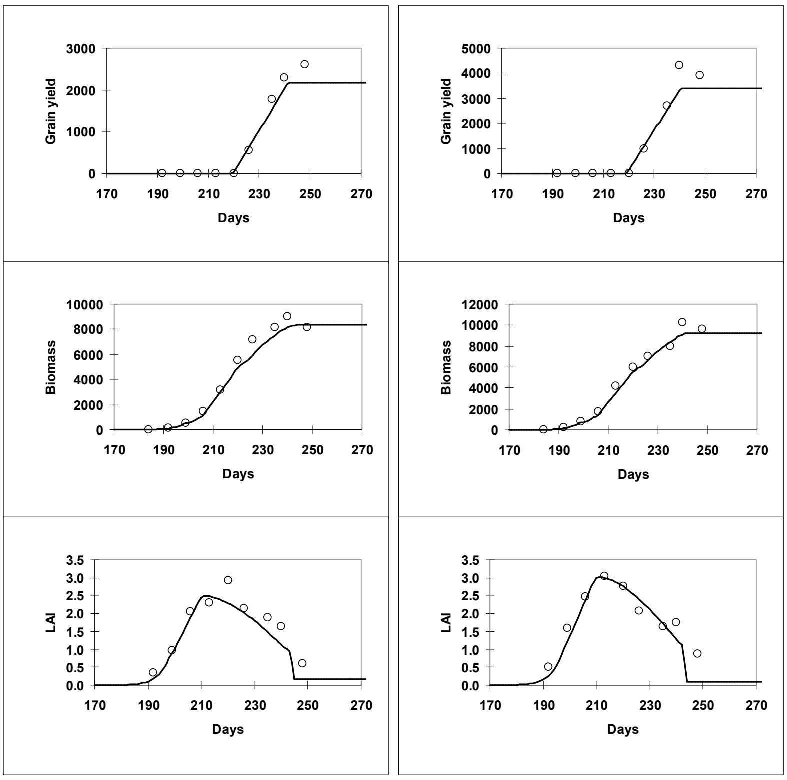


Figure 5. Simulation of grain yield, biomass, and LAI for a high-tillering genotype (WRajPop, left) and a low-tillering genotypes (RCB-IC 911, right), grown at Patancheru in 1995

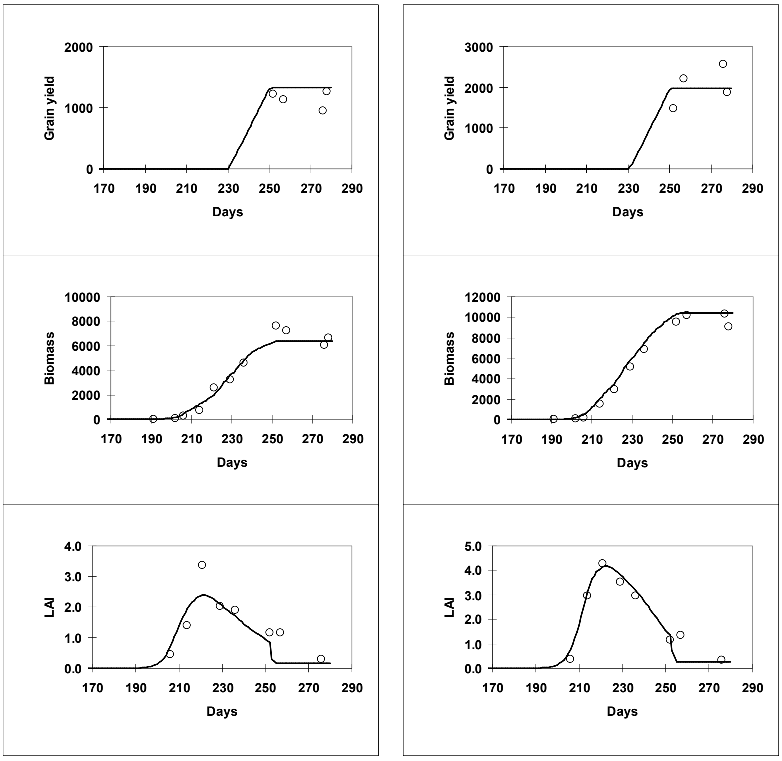


Figure 6. Simulation of grain yield, biomass, and LAI for a WRajPop, grown at Jodhpur, Rajathan, India, with N-fertiliser of 0 kg/ha (lefl) and 40 kg/ha (right) applied.

the low leaf area in the module is thus a result of a reduction in leaf size. Although the module simulates the low leaf area of non-productive tillers adequately (Fig.), the mechanisms behind the simulation are a simplification of reality.

Tiller number

The millet module simulates a maximum of five tillers. Although more tillers are produced throughout the life cycle of the crop, especially if secondary tillers are considered, most of these tillers become non-productive even at low plant densities (Craufurd and Bidinger, 1988a). Their contribution to total GLAI is expected to be relatively small and that to biomass even smaller, as these non-productive tillers do not elongate. They will hence contribute little to photosynthesis, as their leaves are located at the bottom of the canopy. The number of tillers that can be simulated by APSIM-MILLET can be increased, but the errors introduced by simulating a maximum of five tillers are expected to be minor in most circumstances.

List of Publications

1. Akponikpè P.B.I, Michels, K., Bielders, C.L (2008) Integrated nutrient management of pearl millet in the Sahel using combined application of cattle manure, crop residues and mineral fertilizer. *Experimental Agriculture, in press*.

2. Akponikpè P.B.I. (2005) Mathematical simulation of water flow and herbicides transfer in the unsaturated zone. application to the valaisan plain (Rhone, Switzerland). *Bulletin d'Hydrogéologie* No 21 - 2005. Abstract http://capella.unine.ch/chyn/publica_bulletin/bull_21.php

3. Yacouba H., Akponikpè P.B.I., Wima K., Mermoud A. (2003) Impact de la réutilisation des eaux usées épurées par lagunage à macrophytes flottants sur la culture d'aubergine (Solanum melongena). *Annales de l'Université de Ouagadougou. Série C : Sciences de la vie et de la matière. Nouvelle série*. Vol. 001. pp 85-106.

4. Akponikpè P.B.I, Gérard, B., Michels, K., Bielders, C.L Use of the APSIM model in long term simulation to support decision making regarding nitrogen management for pearl millet in the Sahel. Submitted to *European Journal of Agronomy*

5. Akponikpè P.B.I., Gérard B., Fatondji D., Clerget B., Van Oosterom E., Bielders C.L. Effect of sowing date on the development and yield of seven Sahelian millet genotypes under non-limiting water and nutrient supply: experiment and modeling. *To be submitted*

6. Akponikpè P.B.I., Minet J., Gérard B., Defourny P., Bielders C.L. Does spatial dispersion of farmer fields affect the agro-climatic risk at household level in pearl millet-based systems in south-western Niger ? *To be submitted*

International Conferences

Oral presentations

1. Akponikpè P.B.I, Bielders C, Gérard B, Michels K, 2006. Simulation of millet response to combined application of cattle manure, millet residue and chemical fertilizer in the the Sahel using APSIM, 13th Australian Society of Agronomy Conference "Ground-breaking Stuff", The Parmelia Hilton, Perth, Australia, 10-14 Sept., Agricultural Research Western Australia ed. http://www.regional.org.au/au/asa/2006/concurrent/systems/4588_akponikpep.htm

2. Dimes J., Zougmore R., Fatondji D., Akponikpè P.B.I, (2004) Modelling Integrated Soil and Water Management Technologies 5th OSWU Conference Pretoria, July 27-28 2004, R. South Africa.

3. Yacouba H., Akponikpè P. B. I., Compaoré L. M. (2002) Minimizing risks related to the re-use of domestic wastewater treated by floating macrophytes pond

in irrigation of market gardening. International Conference on Environmental Pollution Control and Waste Management (EPCOWM'2002), 7-10 January 2002, Tunis. www.geocities.jp/epcowmjp/EPCOWM2002/588-596yacouba.pdf

Poster presentations

1. Akponikpè P.B.I, Bielders C., Gérard B., Michels K., 2007. Modelling integrated fertility management strategies for pearl millet in the Sahel. 16th international symposium of the international scientific centre for fertilizers (CIEC) "Mineral versus organic fertilization: conflict or synergism?" 16 - 19 september 2007. Gent, Belgium.
2. Akponikpè P.B.I, Saqalli M., Marinho Filho E.A., Gérard G., Bielders C.L., Defourny, Gaspart F (2004). Development of decision support tools for development operators in village communities in the Sahel. Poster presented at the international symposium on Desertification, drought and poverty reduction, June 15th, 2004, Egmont Palace, Brussels, Belgium.

Dissertations (Engineer, MSc.)

1. Akponikpè P.B.I. (2004) Modeling crop production in millet-based systems in the Sahel. DEA dissertation, Bio-engineering. Faculty of Bio-engineering, Agronomy and Environment, Université catholique de Louvain UCL, Belgium.
2. Akponikpè P.B.I. (2002) Mathematical simulation of water flow and herbicides transfer in the unsaturated zone. application to the valaisan plain (Rhone, Switzerland). M.Sc. dissertation, Hydrology and soil physics. Federal Institute of Technology of Lausanne Switzerland (EPFL), Switzerland.
3. Akponikpè P.B.I. (2000) Synthèse sur les techniques d'aménagement des bas-fonds en Afrique de l'Ouest. Mémoire post-grade DESS Ecole Inter-Etats d'Ingénieur de l'Equipement Rural/Ecole Polytechnique Fédérale de Lausanne.
4. Akponikpè P.B.I. (1999) Impact des changements climatiques sur la production agricole : cas du maïs au sud Bénin. Thèse d'Ingénieur Agronome, Option Génie Rural, Eaux et Forêts, Faculté des Sciences Agronomique FSA/Université Nationale du Bénin UNB.

MSc. thesis contributions to this PhD dissertation

1. Minet, J. (2007) Influence de la dispersion du parcellaire sur la gestion du risque climatique au Fakara, Niger. Mémoire de Bio-Ingénieur. Faculté d' Ingénierie Biologique, Agronomique et Environnementale. Université catholique de Louvain UCL, Belgique. 97p + annexes.

2. Dandois Dutordoir, C. (2006) Impact de pratiques de gestion de la fertilité sur les rendements en mil dans le Fakara (Niger). Mémoire de Bio-Ingénieur. Faculté d'Ingénierie Biologique, Agronomique et Environnementale. Université catholique de Louvain UCL, Belgique. 162p + annexes

3. Van Vyve, N. (2006) Caractérisation de la variabilité spatio-temporelle de la pluie au Fakara, Niger. Mémoire de Bio-Ingénieur. Faculté d'Ingénierie Biologique, Agronomique et Environnementale. Université catholique de Louvain UCL, Belgique. 68p + Annexes

4. Ska, O. (2005) Les propriétés chimiques des sols de parcelles cultivées dans le Fakara (Niger). Mémoire de Bio-Ingénieur. Faculté d'Ingénierie Biologique, Agronomique et Environnementale. Université catholique de Louvain UCL, Belgique. 171p + annexes

5. Weynants, M. (2005) Caractérisation des propriétés hydrodynamiques et étude de la possibilité d'agrégation de trois types de sols au Fakara, Niger. Mémoire de Bio-Ingénieur. Faculté d'Ingénierie Biologique, Agronomique et Environnementale. Université catholique de Louvain UCL, Belgique. 100p + annexes

About the author

P. B. Irénikatché Akponikpè was born on 21 December 1973 in Bohicon, Benin (West Africa). He spent his childhood and teenage years in Bohicon until his scientific baccalaureate degree in 1993. He won the same year the Benin national Olympiads of Mathematics (OBM), the 4th PanAfrican Olympiads of Mathematics (PAMO, Dakar Senegal), and two National College Entrance Examinations (Agronomy Sciences and Applied Economics). He dropped the Applied Economics opportunity and chose to enter the Faculty of Agronomy of the Université Nationale du Bénin UNB (now Université d' Abomey Calavi UAC) and graduated in 1999 in Agricultural Engineering and Natural resources management. He successively obtained three post-graduate degrees in "Agricultural hydraulics, DESS" (Irrigation and Drainage engineering 2000, Ecole Inter-Etats d'Ingénieurs de l'Equipement Rural EIER Burkina Faso), in "Hydrology and soil physics, MSc." (2002, Ecole Polytechnique Fédérale de Lausanne EPFL Switzerland) and in "Bio-engineering, agronomy and environment, DEA" (2004, UCL Belgium). He took a PhD position in the project of the "development of decision-support tools for development operators in village communities in the Sahel (Niger)". He started his PhD research in 2004 on the numerical soil, water and crop growth simulation at the Université catholique de Louvain (UCL-Belgium) in collaboration with the International Crops Research Institute for Semi-Arid Tropics (ICRISAT-Niger). In 2000 and 2003, he occupied a research assistant position at EIER now "Institut international d'Ingénierie de l'Eau et de l'Environnement - 2iE, Ouagadougou" on the reuse of treated wastewater in crop irrigation. He has been involved, as freelance consultant, in many research and development projects in Agricultural Engineering since 1999. He is interested in mathematical and computational modeling of the soil-plant-atmosphere system. He is married with one boy child.