


RESEARCH ARTICLE

Effects of contrasted cropping systems on yield and N balance of upland rainfed rice in Madagascar: Inputs from the DSSAT model

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Abstract

In response to the extensive development of upland rice on the hillsides of the Malagasy highlands, alternative cropping systems have been designed based on conservation agriculture (CA). As the promotion of CA in smallholder farming systems is still the subject of debate, its potential benefits for smallholder farmers require further assessment. In the context of resource-poor farmers and low-input production systems, nitrogen (N) is a major limiting nutrient. The effects of contrasted cropping systems have been studied on upland rice yield and N uptake in rainfed conditions: conventional tillage (CT) and CA with a mulch of maize or a legume (*Stylosanthes* or velvet bean). Decision Support Systems for Agrotechnology Transfer (DSSAT) crop growth model was used to quantify the soil N balance according to the season and the cropping system. The lowest yields were obtained in CA with a mulch of maize and were also associated with the lowest crop N uptake. Upland rice yields were higher or equivalent under CA with a legume mulch than under CT cropping systems. The supply of N was considerably higher in CA with a legume mulch than in CT, but due to higher leaching and immobilization in CA, the final contribution of N from the mulch to the crop was reduced although not negligible. DSSAT has been shown to be sufficiently robust and flexible to simulate the soil N balance in contrasting cropping systems. The challenge is now to evaluate the model in less contrasted experimental conditions in order to validate its use for N uptake and yield prediction in support to the optimization and design of new cropping systems.

Keywords: Upland rainfed rice; Nitrogen balance; DSSAT model; Conservation agriculture

Introduction

Upland rice cropping has become a familiar part of the landscape in Madagascar's central highlands (Raboin *et al.*, 2014), spreading over hillsides at middle and high altitudes (from 750 to 1800 m asl.). Ferralsols are the major soil type in this sloping terrain (Grinand *et al.*, 2009). These highly weathered acidic soils contain little soil organic matter and nutrients and are characterized by their low capacity to retain applied nutrients and their high potential to fix phosphorus (von Uexküll and Mutert, 1995). Use of mineral fertilizer is uniformly low in rural Madagascar because of its excessive cost (Minten *et al.*, 2007). To sustain crop production and reduce erosion, conservation agriculture (CA), which involves minimal soil disturbance or no-till, permanent soil cover with crops, cover crops, or a mulch of crop residues and crop rotations, has been proposed to farmers (Husson *et al.*, 2013). As the promotion of CA in smallholder farming

systems is still the subject of debate, its potential benefits for smallholder farmers require further assessment (Corbeels *et al.*, 2014; Giller *et al.*, 2009).

Changing from conventional tillage (CT) to CA cropping systems can have a major impact on N dynamics in the soil (Scopel *et al.*, 2013) as well as on N uptake by rice (Dusserre *et al.*, 2012). Mulching with crop residues reduces soil water evaporation and runoff but increases drainage (Scopel *et al.*, 2005). Part of the soil N supply originates from the decomposition of residues from the previous crop. The N mineralization pattern of crop residues is determined by different factors including the quality of the residues, the type of soil, temperature, moisture, and the location of the crop residues. Crop residues with a high carbon (C) to N ratio, such as straw from cereal crops, immobilize N during the early stages of their decomposition and consequently compete with the following crop for available N in the soil (Mary *et al.*, 1996; Recous *et al.*, 1995). In contrast, residues from legumes – which generally have a lower C to N ratio – may rapidly release their N. Rapid release of large amounts of N may in turn lead to losses through leaching, since crop N uptake is low at the beginning of the growing season (Crews and Peoples, 2005).

Soil N availability is a major limiting factor in low-input farming systems with limited access to mineral N and hence relies to a greater extent on sources of organic inputs and their mineralization (Dawson *et al.*, 2008). The N in the soil that is available during the growing season comes from different origins: the soil itself, organic matter returns (harvest residues, organic amendments), atmospheric inputs (by deposition or precipitation), and fertilizers. Soil N consists of inorganic N at planting time and the integral over the net mineralization rate up to the time of harvest of the crop. Net mineralization is the sum of two components: humus mineralization, which results from the decomposition of stabilized organic matter in the soil, and mineralization of crop residues or organic amendments added to the soil. The N balance in the soil–plant system depends on the main processes that affect the inorganic N content of the soil, that is, mineralization, immobilization, nitrification, volatilization, denitrification, and leaching, and the source/sink effect of the crop, that is, symbiotic N fixation, and absorption of inorganic N. Crop models can be used to integrate N and water dynamics over the growing season. C and N cycling strongly depend on interactions among plant growth processes, soil water dynamics, and soil N dynamics that are highly nonlinear and hence difficult to predict using simple approaches. Crop models, like the Decision Support Systems for Agrotechnology Transfer (DSSAT) model (Hoogenboom *et al.*, 2019; Jones *et al.*, 2003), are based on ecological principles and simulate crop development and growth as a function of weather conditions, soil properties, and management practices. DSSAT has been used to compare the performance of different cropping systems and crop production technologies (Caviglia *et al.*, 2013; Corbeels *et al.*, 2016; Jagtap and Abamu, 2003) and has also been used to assess and analyze the agronomic performance of CA cropping systems (Corbeels *et al.*, 2016; Gerardeaux *et al.*, 2012; Ngwira *et al.*, 2014).

The aim of the work reported here was to study the effects of contrasted cropping systems on upland rice yield and N uptake in rainfed conditions. We used the DSSAT crop model on the assumption that it is sufficiently robust to simulate the main soil N fluxes (mineralization, immobilization, leaching, nitrification, and denitrification) and can be used to predict soil N availability for crops depending on the cropping system. The analysis was performed on data collected in different experiments comparing cropping systems in CT, CA with a mulch of maize, and CA with a legume mulch.

Materials and Methods

Site description

Three experiments were conducted in the vicinity of the village of Ivory, in the mid-west region of Madagascar (19°33'27 S, 46°24'43 E, 960 m asl.) over five consecutive upland rice cropping seasons, 2012–2013, 2013–2014, 2014–2015, 2015–2016, and 2016–2017 (hereafter referred to

as 2013, 2014, 2015, 2016, and 2017). The climatic conditions correspond to a tropical savannah climate, with a unimodal rainfall pattern. Rains start in November and end in April. Cumulative rainfall was 1452 mm in the 2013 cropping season, 1194 mm in 2014, 1814 mm in 2015, 1274 mm in 2016, and 1343 mm in 2017 (Figure 1). Monthly mean temperatures at the site ranged from 23.5 to 25.6 °C during the five cropping seasons. Daily temperatures, solar radiation, and rainfall data were recorded by an on-site automatic meteorological station (ENERCO 404 Series, Cimel, France). According to Jones *et al.* (2013), the soil is classified as Haplic Ferralsol (Oxisol order of the US Soil Taxonomy). Several soil profiles were characterized at the site, and for the experiments, we used a soil profile type containing 20% of clay and 32% of silt. Soil water-holding characteristics were estimated at 0.14 as the lower limit and at 0.28 as the drained upper limit, with total soil N, P, and C concentrations of, respectively, 0.9, 0.6, and 10.8 g kg⁻¹, a pH (water) of 5,

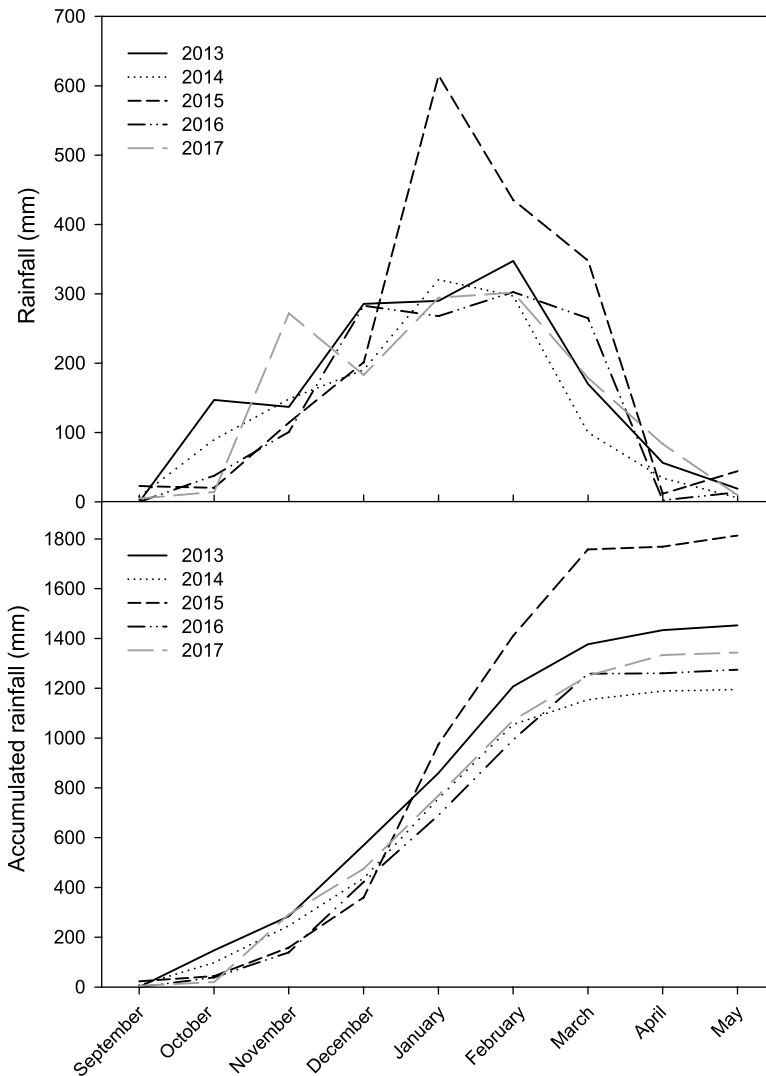


Figure 1. Rainfall and accumulated rainfall (mm) at the experimental site during the five growing seasons. Season 2012–2013: rice sowing date November 30, harvest March 29; Season 2013–2014: sowing date November 20, harvest March 27; Season 2014–2015: sowing date November 29, harvest April 6 in experiment 1; sowing date November 26, harvest March 25 in experiment 2; Season 2015–2016: rice sowing date November 23, harvest March 31; Season 2016–2017: sowing date November 16, harvest March 15.

and a soil bulk density of 1.16 g cm^{-3} in experiment 1, and total soil N, P, and C concentrations of, respectively, 1.0, 0.8, and 12.2 g kg^{-1} , a pH (water) of 5.4, and a soil bulk density of 1.10 g cm^{-3} in experiments 2 and 3, in the top 20 cm of the soil profile.

Experimental designs

The data originate from three separate experiments (Table 1). The same upland rice (*Oryza sativa* L.) variety New rice Africa (NERICA) 4 was sown in all three experiments. A randomized block design was used in all the experiments with six replicates. In experiment 1, upland rice was grown with CT only, and data were used for model calibration. In experiment 2, upland rice was evaluated over a two-year period (2015 and 2016) under three cropping systems (Table 1). In experiment 3, upland rice was evaluated over a one-year period (2017) under two cropping systems (Table 1), but the cropping systems were older. The treatments had been stabilized for five cropping seasons, which allowed us to compare a cropping system with *Stylosanthes* managed as a living cover with total restitution of crop residues versus a cropping system managed conventionally with repeated plowing with total export of residues.

Measurements

Soil inorganic N contents were measured at the beginning of the cropping season, and in experiment 3 only, soil inorganic N content was also measured at the booting, flowering, and harvest stages of upland rice, in the 0- to 80-cm soil layer. Inorganic N (nitrate and ammonium) was measured by continuous flow colorimetry after extraction with a 1M KCl solution.

The number of days to flowering was recorded at the 50% flowering stage, that is, when the anthers extruded from the spikelets in 50% of the plants. In experiment 1 only, for the model settings (genetic coefficients), the leaf area index (LAI) was measured nondestructively in individual plots using a SunScan (Delta-T Devices, Cambridge, UK) placed under the rice canopy, with five readings per plot. In all three experiments, in each plot, whole plants on four hills (0.16 m^2) were cut at ground level and pooled to form one sample. The plant samples were oven dried at $60 \text{ }^\circ\text{C}$ for 72 h and weighed to estimate biomass at flowering (and also at the booting stage in experiments 2 and 3).

In experiment 2 only, the spatial distribution of roots was measured twice, at the booting stage, and at the flowering stage, on four replicates. Using a grid with a $5 \times 5 \text{ cm}$ mesh, root intersections of the upland rice were counted down to a depth of 80 cm over 40-cm-wide soil profiles. Root length density was calculated from the number of root intersections (Dusserre *et al.*, 2009).

At maturity, grain and straw yields were measured in an area (5.4 m^2 in experiment 1 and 20 m^2 in experiments 2 and 3) located in the center of each plot to exclude the edges of the crop. Whole plants from nine hills (0.36 m^2) were harvested in the middle of each plot and separated into straw and panicles. The panicles were hand threshed, and filled spikelets were separated from unfilled spikelets. The dry weights of filled spikelets and straw were determined after oven drying at $60 \text{ }^\circ\text{C}$ for 72 h. As described in Rakotoson *et al.* (2017), the concentration of N in the filled grain and in the straw at harvest was assessed by near-infrared spectrometry (Labspec 4 spectrometer; ASD Inc., Malvern Panalytical, UK) calibrated against a Dumas procedure using a Leco-N-analyzer (FP528; Leco Inc., St Joseph, USA). Crop N uptake was calculated as $(\text{grain yield} \times \text{grain N content}/100) + (\text{straw yield} \times \text{straw N content}/100)$. The agronomic efficiency of N fertilizer (AEN), which represents the amount of grain produced per unit of N applied in $\text{kg}^{-1} \text{ N}$, was calculated as $(\text{grain yield in the treatment with inorganic N fertilization} - \text{grain yield in the treatment with no inorganic N fertilizer})/\text{quantity of N fertilizer}$.

Statistical analyses were performed with SAS 9.3 (SAS Institute Inc., Cary, NC, USA). The generalized linear model procedure was used for analysis of variance. Means were compared

Table 1. Description of the experimental treatments in the different datasets. T or CT: conventional tillage; CAm: no-tillage with a mulch of maize; CAs: no-tillage with a mulch of stylosanthes; uN: unit of N applied in kg h⁻¹; LAI: Leaf area index (m² m⁻²); AGPN: aboveground plant N (kg ha⁻¹); AGB: aboveground biomass (t ha⁻¹); GY: grain yield (t ha⁻¹); RLD: Root length density (cm cm⁻³); SN: Soil inorganic N content (kg ha⁻¹)

Dataset	Year (harvest)	Name	Management			Number of measurements						
			Preceding crop	Soil management	Crop residues	Inorganic N treatment* (urea)	LAI	AGPN	AGB	GY	RLD	SN
Exp. 1 (Calibration)	2013	T 13 N0	Velvet bean (<i>Mucuna pruriens</i> L. DC.)	Tillage	Removal	0 uN	1	2	2	1	0	0
		T 13 N				90 uN	1	2	2	1	0	0
	2014	T 14 N0	Velvet bean	Tillage	Removal	0 uN	1	2	2	1	0	0
		T 14 N				90 uN	1	2	2	1	0	0
	2015	T 15 N0	Bambara groundnut (<i>Vigna subterranean</i> L. Verdc.)	Tillage	Removal	0 uN	1	2	2	1	0	1
T 15 N		120 uN				1	2	2	1	0	1	
Exp. 2 (Testing)	2015	CT 15 N0	Maize (<i>Zea mays</i> L.)	Tillage	Removal	0 uN	0	3	3	1	0	1
		CT 15 N				60 uN	0	3	3	1	2	1
	2015	CAm 15 N0	Maize	No-till	5.7 t ha ⁻¹ of maize	0 uN	0	3	3	1	0	1
		CAm 15 N				60 uN	0	3	3	1	0	1
	2015	CAs 15 N0	Maize	No-till	Removal of maize and add of 6.2 t ha ⁻¹ of Stylosanthes	0 uN	0	3	3	1	0	1
		CAs 15 N				60 uN	0	3	3	1	2	1
	2016	CT 16 N0	Maize	Tillage	Removal	0 uN	0	3	3	1	2	1
		CT 16 N				60 uN	0	3	3	1	2	1
	2016	CAm 16 N0	Maize	No-till	5.3 t ha ⁻¹ of maize	0 uN	0	3	3	1	0	1
		CAm 16 N				60 uN	0	3	3	1	0	1
2016	CAv 16 N0	Velvet bean	No-till	5.7 t ha ⁻¹ of velvet bean	0 uN	0	3	3	1	2	1	
	CAv 16 N				60 uN	0	3	3	1	2	1	
Exp. 3 (Calibration and testing)	2017	CT 17 N	Maize	Tillage	Removal	32 uN	0	3	3	1	0	4
	2017	CAs 17 N	<i>Stylosanthes guianensis</i>	No-till	9.3 t ha ⁻¹ of Stylosanthes	32 uN	0	3	3	1	0	4

*At sowing, a base dressing of 5000 kg ha⁻¹ of cattle manure (N concentration 1.4%), 150 kg ha⁻¹ of triple superphosphate, 130 kg ha⁻¹ of potassium sulfate, and 500 kg ha⁻¹ of dolomite was applied to each hill in all the plots in experiment 1; a base dressing of 100 kg ha⁻¹ of triple superphosphate was applied to each hill in all the plots in experiment 2 and a base dressing of 10 000 kg ha⁻¹ of cattle manure (concentration of 0.93% N) was applied to each hill in all the plots in experiment 3. In experiments 1 and 2, urea was split into three equal amounts and applied at the emergence stage, the tillering stage, and the booting stage. In experiment 3, urea was split into two equal amounts and applied at the emergence stage and the tillering stage.

In experiment 1, the size of the elementary plot was 2 m × 3.8 m with a total of 190 hills; hill spacing was 20 cm × 20 cm, and 4 to 6 seeds were sown in each hill. In experiment 2, the size of elementary plot was 6 m × 7 m with a total of 1 050 hills; hill spacing was 20 cm × 20 cm. In experiment 3, the size of elementary plot was 15 m × 9 m; hill spacing was 30 cm × 20 cm.

according to the least significant difference (LSD) with Fisher's LSD test with a probability level of 0.05. Graphs and regressions were performed with Sigma plot version 12.5 (Systat Software Inc.).

Model setting

DSSAT is a complex nonlinear dynamic model that simulates outputs such as crop development and yield as a function of a large number of input parameters, including plant and soil parameters, whose values are usually estimated based on field experiments, or taken from available literature, or determined through model calibration. To begin a DSSAT simulation, the model is informed about the specific weather, crop, and soil characteristics. The corresponding input files are linked to the main structure of the model, comprising the modules for the field characterization, the initial soil conditions, and the management operations. A detailed description of the DSSAT model with its modules is given in Jones *et al.* (2003). DSSAT has been regularly revised to improve the biophysical representation of soil water, organic matter and nutrient (N and P) dynamics, and their effects on crop growth and yield. The CENTURY soil organic matter model was incorporated in DSSAT by Gijsman *et al.* (2002) to improve simulations of long-term soil C and N dynamics. In 2010, further modifications were made to DSSAT to simulate the effects of tillage and surface crop residues on soil water and organic matter dynamics (Porter *et al.*, 2010).

In this study, we used (1) DSSAT version 4.6, with Crop Environment REsource Synthesis (CERES)-wheat as the crop model that we adapted for upland rice because the plant model settings were more complete than CERES-rice, (2) CENTURY to simulate soil C and N dynamics, and the Ritchie soil–water balance model. The model was parameterized and calibrated for the soil according to the treatments used in experiment 3, and for the crop (genetic coefficients) according to the treatments used in experiment 1 (Supplementary S1). We then validated the model on data from experiment 2 under the CT and CA treatments.

The results of the simulations were analyzed in terms of the N balance components. The main fluxes were N mineralization, N immobilization, crop N uptake, and N leached throughout the crop cycle. Because urea was incorporated in the soil, we assumed that few losses occurred through volatilization, and N losses by denitrification remained low (but were nevertheless included in the N balance). For crop N uptake, model simulations were compared with observed data using the following listed statistics: root mean square error, least-squares coefficient of determination (R^2), and the linear regression (1:1) plot were used as an indicator of whether the models under or overestimated measured crop N uptake.

Results

Grain yield and components, N content, and crop N uptake in contrasted cropping systems

In experiment 2, the results are presented separately for the 2 years due to an interaction with the year. In 2015, there was no interaction between the cropping system and the N application (Table 2). Grain yields were equivalent in CT and CA with a mulch of *Stylosanthes* but lower in CA with a mulch of maize. Higher yields were associated with more panicles per m² in CA with a mulch of *Stylosanthes* and more spikelets per panicle in CT. We observed no effect of the cropping system on the crop N uptake at harvest and neither at flowering. However, the effect of the cropping system was significant on the grain and straw N contents, CT having the lowest grain and straw N contents. Yields obtained without N application were very low regardless of the cropping system (0.78 t ha⁻¹ on average). The effect of N application was significant for all the traits, and the AENs were high: 47.1 kg⁻¹ N in CT, 33.5 kg⁻¹ N in CA with a mulch of *Stylosanthes*, and 28.8 kg⁻¹ N in CA with a mulch of maize.

In 2016, we observed interactions between the cropping system and the application of N (Table 3). Like in 2015, grain yields were equivalent in CT and CA with a mulch of legume

Table 2. Rice grain yield (t ha⁻¹), grain, and straw N content (%), crop N uptake at harvest and at flowering (kg ha⁻¹), number of panicles per m², number of spikelets per panicle, percentage of filled grain (%), and 1000 grain weight (g) of upland rice in experiment 2 in 2015, under the different cropping systems: conventional tillage (CT), no-tillage with a mulch of maize (CAm), and no-tillage with a mulch of Stylosanthes (CAs); and two levels of inorganic N application: with no inorganic N application (N0) and with an application (N) of 60 N kg ha⁻¹. within treatments, means followed by different letters are significantly different according to LSD ($p < 0.05$)

Treatment 2015	Grain yield	Grain N content	Straw N content	Crop N uptake at harvest	Crop N uptake at flowering	Panicles m ⁻²	Spikelets panicle ⁻¹	Grain filling	1000 grains weight
Source of variation									
Cropping system (C)	0.0069	<0.0001	0.0003	0.2665	0.1689	0.0013	0.0368	0.1852	0.3260
N application (N)	<0.0001	0.0002	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	0.0001	0.0112
C × N	0.2200	0.2820	0.5312	0.8434	0.2150	0.7745	0.1466	0.9936	0.0574
Cropping system (combined analysis across N application)									
CT 15	2.38 a	1.16 b	0.55 c	37.9	45.7	219.9 a	55.2 a	69.2	28.8
CAm 15	1.28 b	1.42 a	0.88 a	32.9	36.7	182.9 b	47.0 b	58.5	27.3
CAs 15	1.98 a	1.39 a	0.73 b	43.2	49.4	244.4 a	47.1 b	64.9	27.6
N application (combined analysis across cropping system)									
N0	0.78 b	1.42 a	0.87 a	22.1 b	23.9 b	162.2 b	41.4 b	53.6 b	26.8 b
N	2.97 a	1.23 b	0.56 b	53.9 a	64.0 a	269.3 a	58.1 a	74.8 a	29.0 a

Table 3. Rice grain yield (t ha⁻¹), grain and straw N content (%), crop N uptake at harvest and at flowering (kg ha⁻¹), number of panicles per m², number of spikelets per panicle, percentage of filled grain (%) and 1000 grain weight (g) of upland rice in experiment 2 in 2016, under the different cropping systems: conventional tillage (CT), no-tillage with a mulch of maize (CAm), and no-tillage with a mulch of velvet bean (CAv); and two levels of inorganic N application: with no inorganic N application (N0) and with an application (N) of 60 N kg ha⁻¹. Within treatments, means followed by different letters are significantly different according to LSD ($p < 0.05$)

Treatment 2016	Grain yield	Grain N content	Straw N content	Crop N uptake at harvest	Crop N uptake at flowering	Panicles m ⁻²	Spikelets panicle ⁻¹	Grain filling	1000 grains weight
Source of variation									
Cropping system (C)	<0.0001	0.0031	0.0038	<0.0001	<0.0001	<0.0001	0.0039	<0.0001	0.0100
N application (N)	<0.0001	0.0282	0.0667	<0.0001	<0.0001	<0.0001	0.0892	<0.0001	0.1513
C × N	0.0388	0.0215	0.2079	0.0876	0.9457	0.0009	0.0588	<0.0001	0.4642
C × N (analysis of N application per cropping system)									
CT 16 N0	3.03 b	1.35 b	0.78 a	67.7 bc	48.2 b	205.9 b	86.3 a	82.5 a	24.9 bc
CT 16 N	3.72 a	1.39 b	0.56 b	81.3 b	71.0 a	230.6 ab	77.3 a	86.0 a	25.0 abc
CAm 16 N0	0.64 d	1.38 b	0.88 a	21.6 d	8.0 c	112.2 c	45.2 b	49.8 b	24.1 c
CAm 16 N	2.40 c	1.36 b	0.87 a	57.1 c	33.6 b	227.1 ab	70.0 a	83.2 a	25.2 abc
CAv 16 N0	3.00 b	1.39 b	0.88 a	67.8 bc	38.5 b	225.0 ab	69.9 a	88.2 a	25.8 ab
CAv 16 N	4.17 a	1.52 a	0.82 a	96.7 a	64.9 a	250.3 a	83.6 a	86.6 a	26.2 a

but lower in CA with a mulch of maize. There was a significant effect of the cropping system on all yield components. Higher crop N uptake at harvest was observed in CA with mulch of velvet bean than in CT with N application, although crop N uptakes at flowering stage were equivalent. The effect of N application was not always significant, and AEN was lower than in 2015, except in CA with a mulch of maize, which had a similar AEN in the two seasons: 11.4 kg⁻¹ N in CT, 19.4 kg⁻¹ N in CA with a mulch of stylosanthes, and 29.4 kg⁻¹ N in CA with a mulch of maize.

Table 4. Rice grain yield (t ha^{-1}), grain and straw N content (%), crop N uptake at harvest and at flowering (kg ha^{-1}), number of panicles per m^2 , number of spikelets per panicle, percentage of filled grain (%), and 1000 grain weight (g) of upland rice in experiment 3 in 2017, under the different cropping systems: conventional tillage (CT) and no-tillage with a mulch of *Stylosanthes* (CAs). Within treatments, means followed by different letters are significantly different according to LSD ($p < 0.05$)

Treatment 2017	Grain yield	Grain N content	Straw N content	Crop N uptake at harvest	Crop N uptake at flowering	Panicles m^{-2}	Spikelets panicle $^{-1}$	Grain filling	1000 grains weight
Source of variation									
Cropping system(C)	0.0074	0.8542	0.1588	0.0083	0.0265	0.0189	0.0509	0.0613	0.8302
Cropping system									
CT 17 N	2.57 b	1.51	0.87	59.3 b	68.2 b	194.9 b	63.0	85.7	24.3
CAs 17 N	3.77 a	1.49	1.03	92.4 a	84.6 a	254.9 a	75.1	80.1	24.5

In experiment 3, grain yield and crop N uptakes obtained in 2017, following five growing seasons with the same rotations, were higher in CA with a *Stylosanthes* mulch than in CT (Table 4). Among yield components, only the number of panicles per m^2 differed significantly between cropping systems and was significantly higher in CA than in CT.

Evaluation of DSSAT model and N balance

We evaluated the ability of the DSSAT model to simulate the amount of crop N uptake. There was a good agreement between model simulated and observed values for crop N uptake at harvest and at flowering stage for the three experiments (Figure 2a and b). We also found a good correlation between simulated and observed grain yield (Figure 2c), although grain yield was overestimated for experiments 2 and 3. Factors other than N could have limited grain yield in experiments 2 and 3. Improved base dressing in experiment 1 could explain the higher grain yields observed in this experiment. Figure 2d shows measured and simulated amounts of soil inorganic N in the 0- to 80-cm soil layer in experiment 3 in the 2017 season. Accurate simulation of inorganic N in the soil profile during the cropping season was obtained for CT. DSSAT predicted early and late season amounts fairly well, but slightly underpredicted the amounts for CA in the middle of the season. Nevertheless, the results showed a higher amount of soil inorganic N in CA with a legume mulch than in CT during part of the cropping season.

Simplified N balances simulated by the DSSAT model for experiments 2 and 3 are presented in Figure 3. The N available estimated by the model was related to the yield and crop N uptake (Figure 4). The variations of yield and crop N uptake between cropping system and N application can be largely explained by the variations of N available in the soil as simulated by DSSAT. Between the two seasons in experiment 2, the higher level of N losses in 2015 than in 2016 (Figure 3a and b) was mainly due to leaching because of high rainfall in 2015 (see Figure 1). The N supply was higher in CA than in CT in both seasons (Figure 3a and b), but losses through leaching and immobilization were higher in CA (immobilization was particularly high in CA with a mulch of maize). The higher N losses in CA finally resulted in less difference than expected in available N between CT and CA with a legume mulch.

In experiment 3, a bigger supply of N was observed in CA with a *Stylosanthes* mulch than in CT (Figure 3c, N input of 213 kg ha^{-1} in CT, 308 in CA) concomitantly with higher simulated N losses in CA, thus reducing the difference in soil available N between CT and CA (available N (N input – N losses) of 127 kg ha^{-1} in CT and 153 in CA).

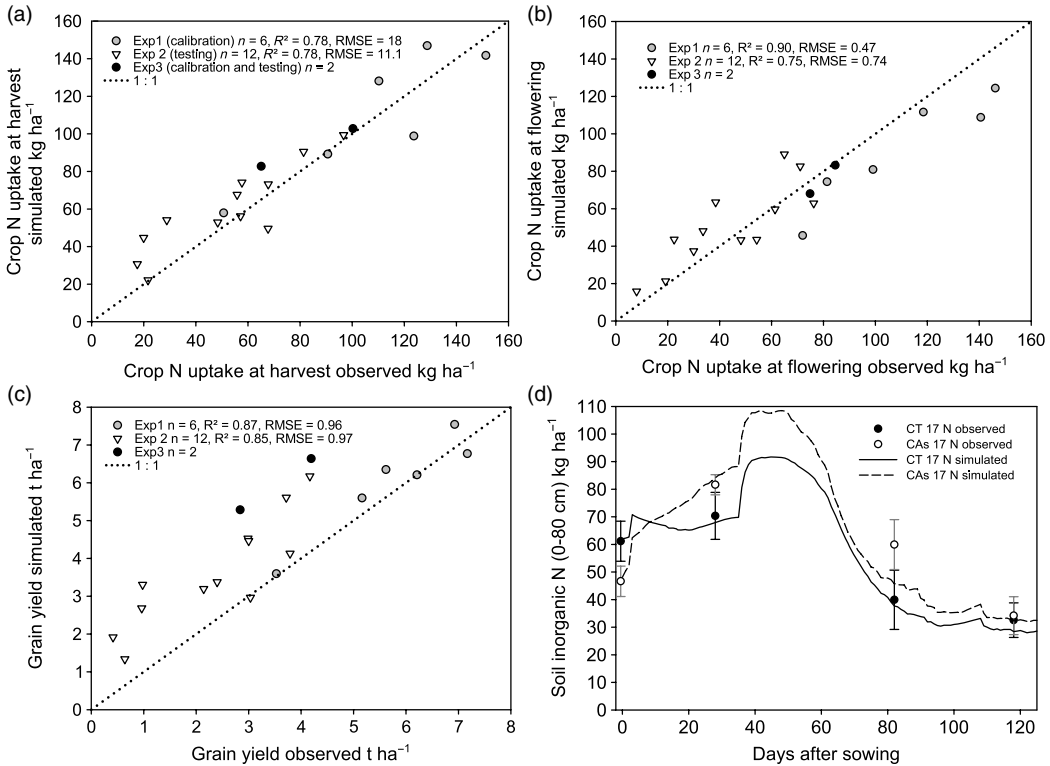


Figure 2. Comparison of observed and simulated crop N uptake at harvest (a), at flowering stage (b), grain yield (c) in the different experiments, and soil inorganic N content (d) in experiment 3. The dotted line is the 1:1 relationship.

N uptake and utilization efficiencies

Using all the experiments, an overall linear relationship was observed between simulated available N in the soil (0–80 cm) and crop N uptake observed at harvest, with an R^2 of 0.86 (Figure 5a, $y = -20.1 + 0.79x$). The slope of the relationship between crop N uptake and available N is the N uptake efficiency (NUPE) of the upland rice variety NERICA 4. A quadratic relationship was obtained between observed grain yield and crop N uptake at harvest, with an R^2 of 0.93 (Figure 5b, $y = -0.365 + 0.057x - 3.82 \times 10^{-5} x^2$). The slope of the relationship between grain yield and crop N uptake is the N utilization efficiency (NUTE) of the upland rice variety NERICA 4.

Discussion

Upland rice yield

In experiment 1, conducted only under CT, the grain yields obtained were high (between 4 and 7 t ha⁻¹, cf. Figure 2c), probably due to the application of an improved base dressing. In experiment 2, upland rice yields were higher or equivalent under CA with a legume mulch than under CT cropping systems, but lower under CA with a mulch of maize. It is recognized that keeping the residues of the previous crop may lead to N immobilization. This may be particularly limiting under low-input management systems when there are no minerals available to balance N immobilization and when large quantities of residues remain on the soil surface (Baldé *et al.*, 2011). Lower yields in CA with a mulch of maize were associated with a reduction in almost all yield components. Whereas, the differences between CT and CA with a legume mulch cropping systems were less contrasted except in experiment 3. In experiment 3, CA with a mulch of Stylosanthes

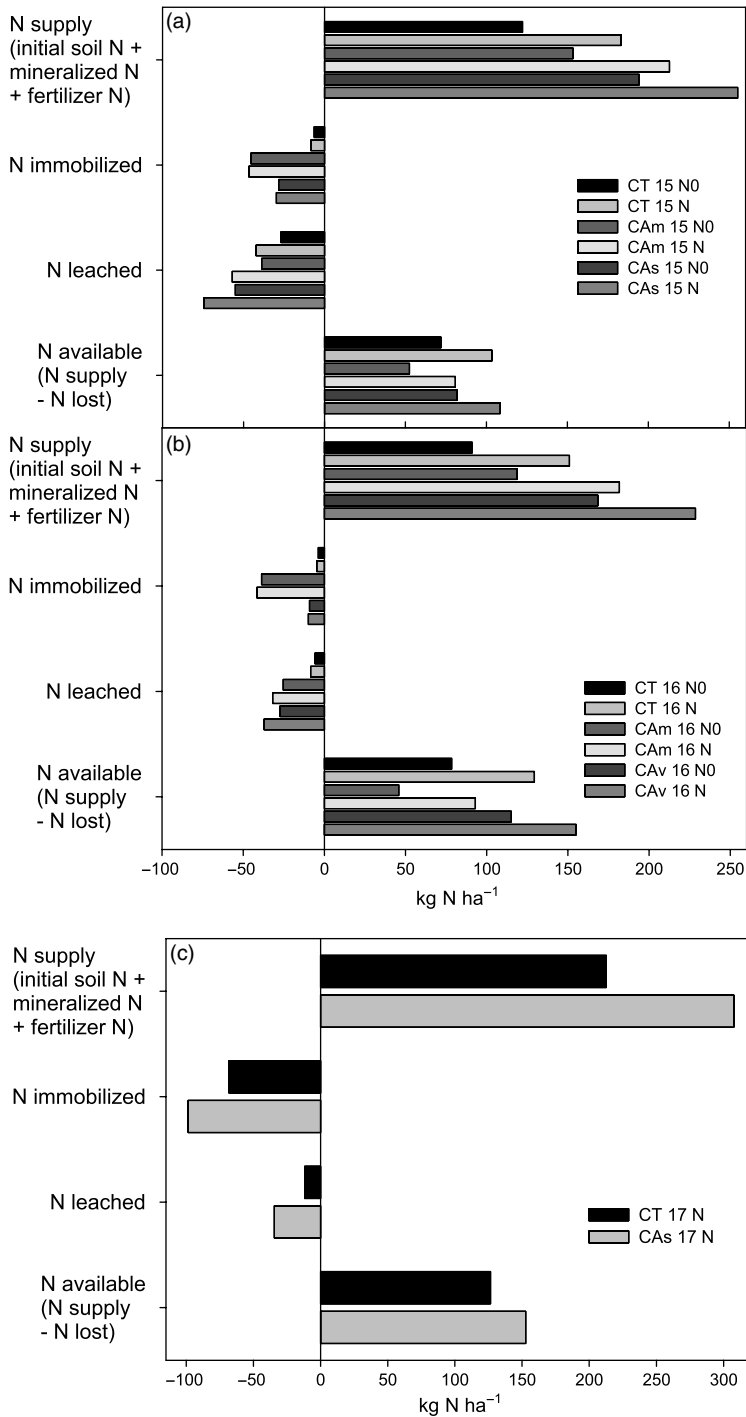


Figure 3. Simplified N balance simulated by the DSSAT model for experiment 2 in 2015 (a), in 2016 (b) and in experiment 3 in 2017 (c), with conventional tillage (CT), no-tillage with a mulch of maize (CAm), no-till with a mulch of *Stylosanthes* (CAs) or no-till with a mulch of velvet bean (CAv), and two levels of inorganic N application: no inorganic N application (N0) and with an application (N) of 60 N kg ha⁻¹ in 2015 and 2016 or 32 N kg ha⁻¹ in 2017.

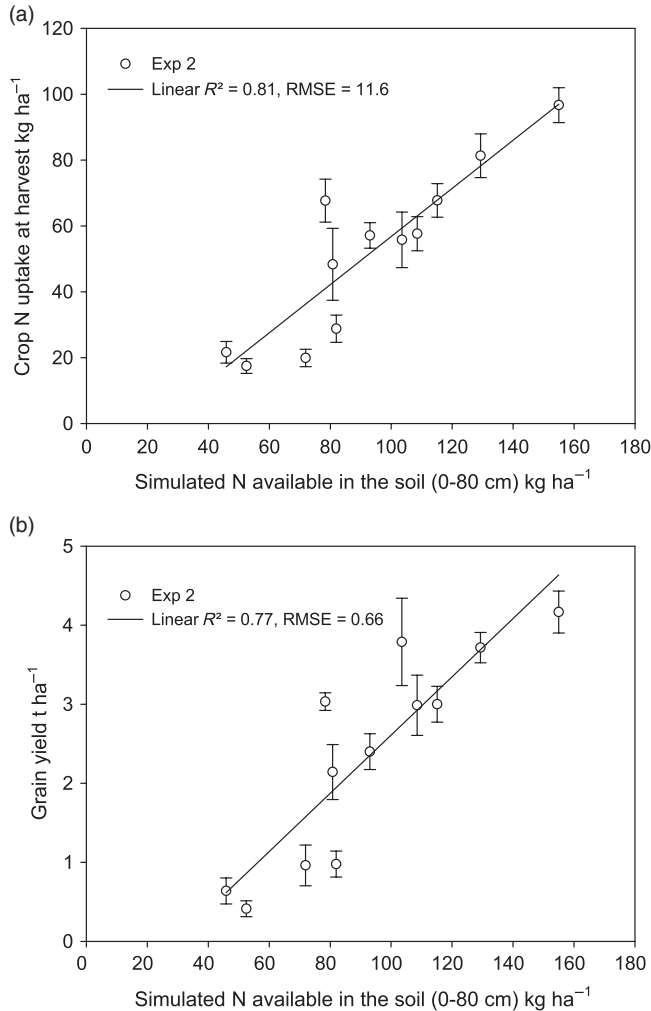


Figure 4. The relationship between observed crop N uptake at harvest and simulated N available in the soil (a) and the relationship between observed grain yield and simulated N available in the soil (b) in experiment 2. The bars represent standard errors.

yielded significantly better than CT, five years after the conversion to CA, as a result of an increased number of panicles per m² and number of spikelets per panicle. The improvement of yield after conversion to CA in combination with legume rotation is a long-term process (Rusinamhodzi *et al.*, 2011).

Relevance of DSSAT crop growth model in simulating rainfed rice under contrasted cropping systems

DSSAT has already been used to assess and analyze the agronomic performance of CA cropping systems (Corbeels *et al.*, 2016; Gerardeaux *et al.*, 2012; Ngwira *et al.*, 2014), and these studies demonstrated that DSSAT can be used to simulate crop responses to CA, in particular by simulating the effects of mulching on the soil water balance. Here, we show that DSSAT is sufficiently robust and adaptable to simulate the soil N balance in contrasting cropping systems and can be used

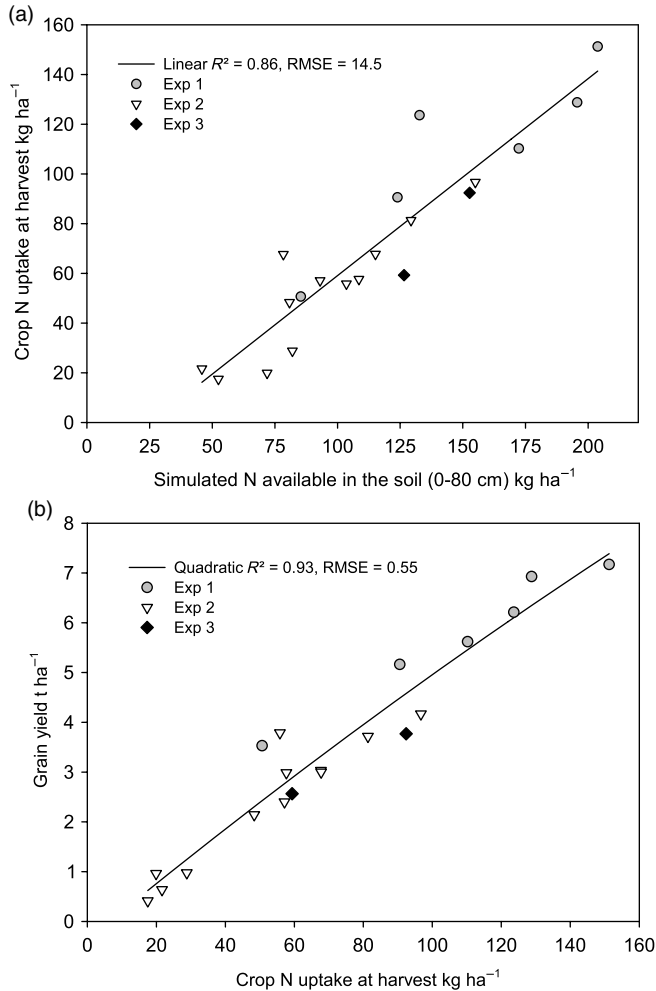


Figure 5. The relationship between observed crop N uptake at harvest and simulated N available in the soil (a) and the relationship between observed grain yield and crop N uptake at harvest (b) for all experiments.

to predict N uptake and yield. In our case, we did not make any changes to the model settings for the different cropping systems, whereas to reproduce observed maize yields under the CT versus CA treatment, Corbeels *et al.* (2016) had to restrict optimal root development in the model in the CT treatment (due to the existence of a plow pan).

Interpretation of N flux with DSSAT

Leaching was a major N flux. The valorization of the soil N supply by the crop depended on N leaching, which itself was influenced by the rainfall pattern. N losses are likely to be high under the heavy rainfall typical of the tropics. According to the DSSAT N balance, N losses by leaching accounted for between 14 and 53% of the total N losses under CT, between 22 and 51% under CA with mulch. Greater drainage can be expected under CA with mulch than under CT due to the reduction of surface water runoff and soil evaporation rates. The phenomenon of increased deep drainage under CA compared with CT has already been observed in the field and simulated in Brazilian oxisols (Scopel *et al.*, 2004). Deep drainage involves a risk of nutrient leaching.

The large pool of easily decomposable organic compounds from surface residues adds to the risk of nutrient leaching in CA systems.

Legume fallows are expected to supply increased N inputs to the system. In this study, a gain in N available in the soil was obtained with the application of a legume mulch, but the gain depended on the type of legume and on the season (Figure 3). Studies involving the application of ^{15}N labeled legume residues have shown that between 10 and 30% of the legume N is commonly taken up by the following crop (Crews and Peoples, 2005). It has also been shown that *Stylosanthes* fallow can increase rice yield compared to a natural fallow (Becker and Johnson, 1999; Saito *et al.*, 2006). These different authors reported that the increase in rice yield was related to the amount of N inputs originating from the legume fallow. In a recently installed experiment on a rice-*Stylosanthes* crop rotation at the same site as the present study, Zemek *et al.* (2018) concluded that, although *Stylosanthes* can fix significant amounts of N_2 and produce high amounts of dry matter, the final N contribution to rice was small (^{15}N recoveries in rice ranged from 5 to 8% from a *Stylosanthes* mulch). According to Zemek *et al.* (2018), the contribution of the *Stylosanthes* mulch to the following rice crop was small because its decomposition was incomplete and the N released was mainly present in a form that is not available to plants because the *Stylosanthes* mulch was placed on top of the soil and also due to its rather high C:N ratio (55).

N uptake

A previous experiment revealed the existence of significant genetic variability for N use efficiency (NUE) and its components (NUPE and NUTE) among a set of 13 varieties representative of the genetic diversity of the tropical japonica group adapted for upland cultivation at mid-altitude in Madagascar, including the variety NERICA 4 (Rakotoson *et al.*, 2017). The relationship between NUE and agronomic and N-related traits differed from one year to the next, illustrating the plasticity of the contribution of the different agronomic traits to NUE as a function of the contrasted climatic conditions (particularly the rainfall distribution pattern). Here, we were able to estimate NUPE and NUTE for NERICA 4 variety by combining the results of different experiments and modeling (cf. Figure 5).

The cropping system affects crop N uptake and/or N content (Tables 2, 3, and 4). We hypothesize that the observed differences in grain and straw N content are due to differences in crop N uptake dynamics. It has already been shown that tillage has significant effects on the accumulation of aboveground biomass and N uptake in rice, particularly before and after the heading stage (Huang *et al.*, 2012). In an experiment in which no significant difference in grain yield and total aboveground biomass was observed between CT and no-tillage, Huang *et al.* (2012) showed that N uptake was 27% lower before heading but 73% higher after heading in the no-till system than in CT, indicating that N uptake was delayed in no-till rice. According to these authors, no-till rice roots were subject to an adverse environment in the early growth stage, with significant soil compaction of the 5- to 10-cm soil layer due to the lack of tillage. However, the negative effects of no-tillage on aboveground biomass production before heading were offset by its positive effects on aboveground biomass accumulation after heading. In late growth stages, given the higher rate of N available in the soil due to mineralization of the mulch, crop N uptake was higher under CA than under CT. This led to higher N content at harvest, particularly in the grain, under CA than under CT. Root length density measurements were performed on experiment 2 in both seasons (data not shown). A high variability between repetitions resulted in few significant differences between treatments, but the general tendency showed a greater development in the top-soil in CT and a greater vertical root development in CA. Greater and faster root development at the beginning of the upland rice crop cycle after the soil was plowed and greater vertical root development before the heading stage with no-tillage have already been observed in colder conditions (Dusserre *et al.*, 2012).

Conclusion

The results of our different experiments indicate that N uptake by the upland rice crop can be optimized in CA cropping systems through various agronomic lever such as mulch quality (C–N ratio) or the application of mineral N. In these experiments, the performance of CA with a mulch of legume was always equivalent or superior to CT, but all these CA cropping systems were based on a rotation with a cover crop that does not produce edible grains (velvet bean or *Stylosanthes*). The focus should now be on optimizing rotations that associate maize and legumes especially if they are edible (maize and rice bean, maize and cowpea . . .), if adoption by smallholders is expected. The objectives would be to determine the best balance between the two crops, the optimum quantity of mulch that should be left over the soil, and the optimal quantity, timing, and splitting for the application of mineral N. Crop models such as DSSAT should be very helpful in that process.

DSSAT provided relevant N balance simulations that help dissect the effects of contrasting cropping systems, that is, the effect of CA versus CT including the effect of restitution versus non-restitution of residues, and the effect of contrasted mulch quality in CA between legume and maize crop residues. In our set of experiments, N losses estimated by the model were higher in CA than in CT in a given season, as a consequence of increased infiltration and leaching. Higher amounts of immobilized N were estimated in CA with mulches than in CT, and in CA with a mulch of maize than in CA with legume mulch. The model also seems to be able to distinguish between different types of legume as estimated N immobilization was higher with *Stylosanthes* than with velvet bean. Indeed, the challenge is now to evaluate the model in less contrasted experimental conditions to see if it can capture and explain finer variations between cropping systems: CT and CA cropping systems both with legume rotation and restitution of residues, different CA systems comparing the quality of different legume mulches, and so on. Only then will it be possible to use the model as a tool to design and optimize cropping systems.

Supplementary material. To view supplementary material for this article, please visit <https://doi.org/10.1017/S0014479720000010>

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