

# Positive effects of climate change on rice in Madagascar

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**Abstract** Food security in many countries is threatened due to rapid population growth. Rising temperatures and carbon dioxide, rainfall irregularity, and global warming may have serious consequences on rice production and hence food security. However, there is limited knowledge on the precise effects of global warming on crops, in particular on rice which is a major staple crop and contributor to food security. Most reports have focused on irrigated rice in India or China but much less is known about rainfed rice cropping systems in Madagascar. In the Malagasy highlands, the most populated part of Madagascar, land pressure has led to saturation of irrigated lands and the adoption of rainfed cropping systems on hilltops. The present article reports the impact of various climate changes on rice productivity in four cropping systems using the CERES-Rice model. The cropping systems include two tillages components, hand-plowed and no-tillage, and two fertilization rates: low and high nitrogen. A locally adapted rice cultivar was calibrated and validated using a dataset based on experiments conducted over a 6-year period. Daily weather data were

generated for a set of 90 virtual years, from 2010 to 2099. Our results show that no-tillage systems have no advantage for climate change issues. Nitrogen was a major constraint for crops in hand-plowed and no-tillage systems. We found negative effects of climate change on soil carbon and nitrogen. By contrast, we found positive effects of temperature and increased CO<sub>2</sub> on rice growth. The overall effects on rice yields are positive under the most pessimistic climate change scenarios but we demonstrate that the sustainability of these systems is threatened.

**Keywords** Rainfed rice · Cropping system · Climate changes · Malagasy highlands · Yield prediction · Weather generator

## 1 Introduction

Rice is the staple food for half of the world's population (Khush 2005). Mounting pressure on natural resources and the expected 50% increase in the world population in the next half century (Cohen 2003) mean that the effects of climate change on rice productivity are a crucial issue, especially in Madagascar where food security has yet to be achieved.

The rise in temperature, carbon dioxide, and irregular rainfall may have serious effects on crop production and hence in food security. Rice systems need to be managed so that they are less vulnerable to climate extremes. This requires new plant varieties that are (1) adapted to higher temperatures and (2) tolerant to other abiotic stresses, particularly submergence, drought, and salinity, especially in rainfed lowland rice cultivation areas in Asia and Africa. Most research efforts will focus on irrigated areas, where rising temperatures could result in serious yield losses and where water scarcity may become more widespread.

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Highland rainfed rice may not suffer in the same way as other rice cultivation systems around the world. An increase in temperature will modify the phenology of rice crops and could be beneficial where low temperatures are currently a limiting factor to rice growth. On the other hand, higher temperatures and an increase in wind speed combined with drought during critical growth stages could have detrimental effects on yield. We therefore considered it useful to assess the consequences of global warming on rice productivity in the Malagasy Highlands.

The Vakinankaratra region in the central highland region is the most densely populated area of the country, with more than 80 inhabitants/km<sup>2</sup> (Barrett 1997). Smallholders traditionally grow irrigated or rainfed lowland rice, mostly landraces, wherever possible, and admirable development advances have been made in inland valleys and on hillside terraces. But the possibilities for expanding lowland rice cultivation areas are almost exhausted (Kull 1998). Thus, the challenge to meet the growing demand for rice relies on the intensification of lowland rice cultivation and on the development of new rice-based production systems. In the mid-1980s, CIRAD and the Malagasy National Institute of Agricultural Research (FOFIFA) launched a research program for the highlands with the aim of pushing forward the frontier of rice growing areas in the uplands. This led to the release in the early 1990s of new upland rice varieties suitable for cultivation on hillsides (“Tanety”), where farmers formerly grew corn, beans, or cassava. As early as 4 years after the appearance of the first new varieties, a survey showed that more than 1,500 ha were already being cultivated with upland rice at elevations above 1,250 m as a result of a vast network of on-farm trials and participatory evaluation. The same survey showed that more than 9,000 farmers (about 10% of all farmers in the target area) had started cultivating upland rice. Today, upland rice is part of the Malagasy Highland’s landscape and new breeding challenges have arisen.

Due to ecosystem fragility, upland crop production systems based on conventional tillage could become unsustainable, partly because of the erosion that affects upland rice by washing away the upper soil horizon, while lowland rice could be affected by silting. Direct-seeding mulch-based cropping systems (DMC) have already proved their worth in countries such as Brazil, Benin, Laos, and Vietnam; they ensure permanent protection of the soil and hence open up new possibilities for enhancing the sustainability of upland rice cropping systems.

With the aim of limiting the physical and chemical erosion of soil hills, the non-governmental organization TAFE and the French institute CIRAD (Center for International Cooperation in Agricultural Research for Development), have been testing DMC systems for the last 15 years in Madagascar, particularly in Vakinankaratra region. Under DMC, cover plants (live or dead) and crop residue mulch can play different roles: reduce

erosion (Scopel et al. 2005), runoff (Findeling et al. 2003), and losses by direct evaporation (Scopel et al. 2005) while increasing annual C and N rates by forming a surface horizon with a high humus rate, thus increasing biological activity (Rabary et al. 2008).

General circulation models used to study climate change produce different results concerning changes, especially at the regional scale (Mitchell et al. 1990). For Madagascar and South Africa, general circulation models predicted an increase in temperature of 1.8°C year<sup>-1</sup> to 4.7°C year<sup>-1</sup> for a doubling of CO<sub>2</sub> (IPCC 2007). This range could make a considerable difference in the assessment of potential impacts. Such models are also known to be weak in evaluating rainfall predictions. These uncertainties need to be kept in mind when interpreting the possible impact of climate change on rice production.

Mechanistic crop models are routinely used to assess the impacts of climate changes on their outputs. Several models are available for rice, including ORYZA1N (Aggarwal et al. 1997), ECOMERISTEM (Luquet et al. 2006), and CERES-Rice (Nain and Kersebaum 2007). Among these models, CERES-Rice is the only one that combines an acceptable set of physiological bases, the possibility to simulate rotations with other crops, and a sequential mode for long-term analysis of cropping systems. The increase in growth rates and sink size due to CO<sub>2</sub> enrichment will lead to a greater demand for N mobilization during grain filling. We thus considered that a good simulation of soil N and C dynamics would be a decisive benefit. The Decision Support System for Agrotechnology Transfer (DSSAT) suite of models (Jones et al. 2003) uses such a model with its Century sub-model.

The objective of the present study was to determine the impact of climate changes on rice production under different cropping systems using CERES-Rice and to examine the uncertainty in impact assessment.

## 2 Material and methods

### 2.1 Experiments

The experiments were conducted in Andranomanelatra (19° 47' S, 47°06' E, 1,642 m above sea level) in the Malagasy Highlands. Annual rainfall averages 1,475 mm and falls mainly in the wet season from November to April. Annual temperature ranges are (1) daily maximum from 20°C to 26°C, daily minimum from 6°C to 15°C, and daily average from 12°C to 18°C. The soil is classified as a clayey Andic Dystrustept (soil survey staff, 2003) or a ferralsol according to the FAO classification (FAO 2006). The study was conducted at an experimental station managed by the Malagasy National Institute of Agricultural Research (FOFIFA) in partnership with CIRAD. The design consisted

of completely randomized blocks with four replications on long-term grassland dominated by *Aristida* species. The experiments consisted of a factorial combination of tillage and N treatments in 2003, 2004, 2005, and 2006 and a factorial combination of tillage and sowing dates in 2010. The tillage treatments included conventional tillage with removal of residues (LAB), and with direct-seeding mulch-based cropping systems (DMC), with both replicated four times in 100-m<sup>2</sup> plots. Our study focused on upland rice (*Oryza sativa*). Upland rice was sown after a rotation of beans followed by oats. Residues of the preceding crop (beans and oats) were left on the soil surface (0.5 kg dry matter m<sup>-2</sup>) after harvest (in February to March for beans and in June for oats) in the DMC system. No additional application of crop residues was made in either management treatment. Six to eight rice seeds (cultivar FOFIFA 161) were sown manually in hills with a 20×20 cm spacing (25 hills per m<sup>2</sup>). The rotation was rice (*O. sativa*) the first year followed by common beans the second year, after the beans were harvested, oats (*Avena sativa*) were sown. Each season, both rotation crops (rice and common beans) were included in the experiment. Herbicide (glyphosate and 2,4-dichlorophenoxy acetic acid) was applied before planting in DMC plots, whereas weeds were removed by hand in tilled plots. Fertilization consisted of cattle manure (5 Mg ha<sup>-1</sup>, i.e., 17 kg N ha<sup>-1</sup>), NPK (11% N, 22% P<sub>2</sub>O<sub>5</sub>, 16% K<sub>2</sub>O) fertilizer (300 kg ha<sup>-1</sup>), and dolomite (CaMg(CO<sub>3</sub>)<sub>2</sub>, 500 kg ha<sup>-1</sup>), and in both management treatments the fertilizer was placed in the planting hole with the seed, and urea (46%; 50 kg ha<sup>-1</sup>) was applied as a top dressing with urea in a row-banded application 35 and 65 days after seeding. Weeds were controlled by hand weeding, and an insecticide (Gaucho®) was applied at sowing. Experiments 2003 and 2004 were used for the model calibration (see below) and experiments 2005, 2006, and 2010 for model validation.

## 2.2 Modeling

The DSSAT 4.5 cropping system model (DSSAT-CSM) beta version (Jones et al. 2003) was used for this study. With this version, the experimental mode can be used for annual calibrations and validations and the sequential mode for multi-annual cropping systems. DSSAT-CSM uses a set of codes to simulate soil nitrogen, water, and carbon dynamics, while crop growth and development is simulated by plant models (CERES, CROPGRO, SUBSTOR, etc.; Hoogenboom and White 2003). Weather data used for our simulations were rainfall (mm day<sup>-1</sup>), minimum and maximum air temperature (°C), solar radiation (MJ m<sup>-2</sup> day<sup>-1</sup>), dew point temperature, wind speed, and potential evaporation (mm d<sup>-1</sup>). The data were recorded on a Cimel automatic weather station (ENERCO-400) located 50 m from the experimental plots.

Soil inputs included albedo, photosynthesis factor, pH, drainage, and runoff coefficients set at 0.14, 1, 4.9, 0.25, and 81, respectively. The model also required the water holding capacity, saturated hydraulic conductivity, bulk density, nitrogen content, and organic carbon for each soil layer. The genetic parameters required for CERES-Rice and oats were P1 (duration of the basic vegetative stage) P2O (critical photoperiod of the longest day length), P2R (delay in panicle initiation as a function of P2O), P5 (duration of grain filling), G1 (number of spikelets), G2 (single grain weight), G3 (tillering coefficient), and G4 (temperature tolerance coefficient). Bean growth and development was simulated by CROPGRO with its own set of genetic parameters.

## 2.3 Calibration and validation

The dataset for calibration came from the experiments conducted in 2003 and 2004. In our calibration procedure, we varied parameter values to minimize the RMSE (Table 1).

Generalized likelihood uncertainty analysis (GLUE), a Bayesian method, allows information from different types of observations to be combined to estimate probability distributions of parameter values and model predictions (He et al. 2010). GLUE software was used to calibrate the genetic coefficients to fit the phenology variables through anthesis and maturity dates and growth variables through the maximum leaf area index, crop weight, yield, grain number, and dry weight at maturity. Approximately 8,000 runs were made with GLUE.

After the automatic procedure, we refined the calibration with a manual and iterative approach according to Godwin et al. (1989). The genetic parameters were refined to fit time series observation data (LAI, number of tillers, dry weight of aerial parts).

The validation dataset was not the same as that used for calibration. For validation, we used data from 2005, 2006, and 2010. However, the DMC treatment in 2005 was

**Table 1** Variables used for the CERES-Rice calibration

	Calibration			Validation		
	R <sup>2</sup>	RMSE	obs	R <sup>2</sup>	RMSE	obs
ADAT	0.81	2.0	8	0.77	8.2	7
MDATE	0.89	3.3	8	0.59	10.5	8
CWAM	0.81	5,070	8	N.A.		
H#AM	0.77	2,588	8	N.A.		
HWAM	0.88	941	8	0.82	499	10
LAIX	0.60	1.30	8	N.A.		

ADAT anthesis date, MDATE maturity date, CWAM crop weight at maturity, H#AM number at harvest maturity, HWAM harvest weight at maturity, LAIX maximum LAI, R<sup>2</sup> coefficient of correlation, RMSE root mean square error, obs number of observations

removed from the dataset since the crop had been infested by soil insects such as white grubs and consequently had very low densities and yields.

## 2.4 Climatic changes

IPCC made several predictions for climate changes for the 2080–2099 period (IPCC 2007). These predictions account for different scenarios representing global policies and human demography. There is also an inner variability of predictions in each scenario depending on the uncertainties of the models. For example, temperature is assumed to rise from 1.8°C to 4.7°C in the A1B scenario. We decided to conduct a sensitivity analysis for (1) no climate change (control), (2) a gradual increase in CO<sub>2</sub> up to 750 ppm and a rise in temperature of 0.15°C per decade, and (3) a gradual increase in CO<sub>2</sub>, a rise in temperature of 0.5°C per decade, and a reduction in rainfall (−0.2 mm day<sup>−1</sup>) from December to February. The increase in CO<sub>2</sub> and the relatively small increase in temperature could be considered as an optimistic scenario since it is supposed to favor rice growth. On the contrary, a high increase in temperature combined with reduced rainfall might have detrimental effects, even if CO<sub>2</sub> increases, as rice may experience severe water stress due to a major increase in evaporative demand. We call this the pessimistic scenario.

SIMMETEO model uses monthly climatic means of the number of wet days, precipitation, solar radiation, and maximum and minimum temperature as well as regression equations to compute conditional means, standard deviations, and precipitation parameters (Geng et al. 1986; Pickering et al. 1994). Monthly means of solar radiation and temperature for dry and wet days and their standard deviations are also required for weather generation. Details on the parameter estimation methods used in SIMMETEO can be found in Soltani and Hoogenboom (2003). The weather utility program WeatherMan (Pickering et al. 1994), which embodies SIMMETEO, was fed with 20 years of consecutive data (1990 to 2010). It generated a 90-year climatic dataset (2010 to 2099). Then, we changed the temperature, rainfall, and CO<sub>2</sub> values according to the scenario treatments.

## 3 Results and discussion

In this study, we assumed that rice crops were not limited by weeds, pests, and diseases. This assumption has limitations and our results thus only revealed “an evolution of yields under ideal biotic conditions”. Moreover, weather events like strong winds, typhoons were disregarded, although it is common knowledge that they have detrimental effects on yields in this region. Our results focus on the

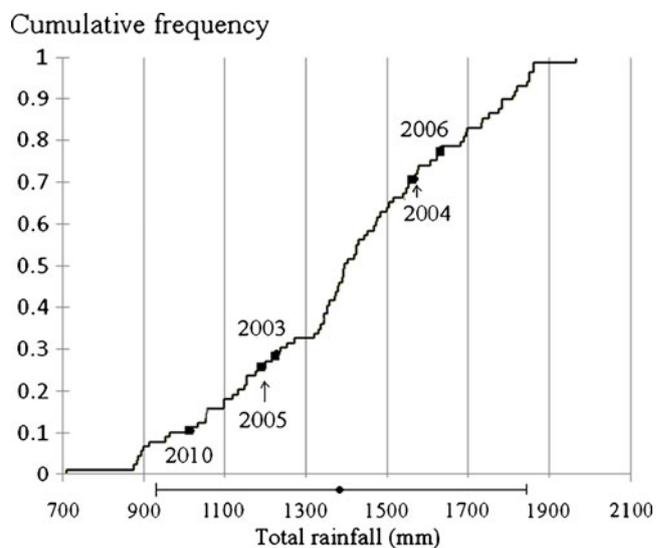
consequences for rice crops. Bean and oat yields were simulated but they are not the central issue of this paper.

### 3.1 Climatic data during the field experiments

Figure 1 represents the total rainfall during the growing seasons (square dots) and the distribution of the total rainfalls generated. The season 2010 was very dry, with nearly 25% less rain than average. The monthly ambient air temperature ranged from 13.4°C to 18.7°C over the seasons. Rainfall in 2006 was 17% greater than average, with 700 mm in January, almost twice the usual amount of rainfall.

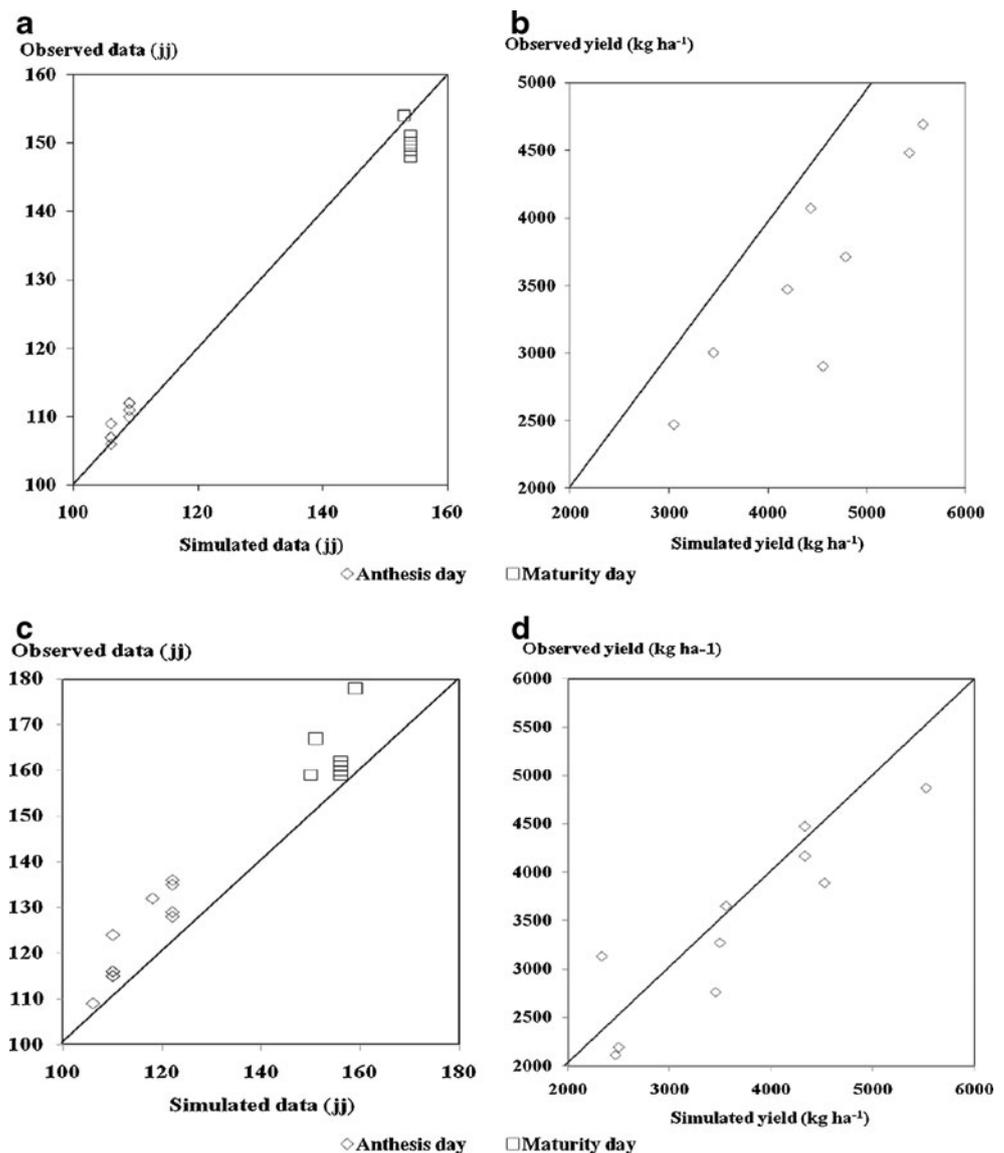
### 3.2 Calibration and validation

Calibration with the GLUE model gave a set of genetic coefficients. The final values of the eight genetic parameters for rice genotype F161 are: 371.6, 66.4, 342.4, 12.0, 51.8, 0.021, 0.77, and 0.87 for, respectively, the basic vegetative phase (P1), the critical photoperiod (P20), the delay of panicle initiation for each hour increase above P20 (P2R), the grain filling duration (P5), the potential spikelet number coefficient (G1), the single grain weight (g) under ideal conditions (G2), the tillering coefficient relative to IR64 cultivar under ideal conditions (G3), and the temperature tolerance coefficient (G4). These were obtained by fitting the model against data observed during the experimental trials (Table 1, Fig. 2a and b). A value of 0.77 was obtained for G3 to account for the low tillering capacity of this cultivar. Automatic calibration with GLUE confirmed



**Fig. 1** Distribution of total rainfall over the 90-year period (2010–2099) simulated by SIMMETEO (line), for the experimental years in 2003, 2004, 2005, 2006, and 2010 (square dots) and the average  $\pm$  standard deviation of total rainfall measured (1990–2010; circle dot and bar line under X-axis) in Kobama, Madagascar

**Fig. 2** Simulated and observed data used for calibration, phenology (a), and yield (b) and validation, phenology (c) and yield (d)



the adaptation of F161 to cold environments by setting the G4 value at less than 1.

Validation was done by assessing the performance of the model with a different dataset using the root mean square difference and linear regression analysis between observed and simulated data. The comparison of observed and measured phenological events and productivity was acceptable (Table 1 and Fig. 2c and d) except for the slightly different maturity dates where the dates were under predicted. This variation in predicted maturity corresponds mainly to DMC treatments and has already been observed on rice in other parts of the world. This is probably due to thermal variations (Yun 2003) (Sarkar and Kar 2008). The high values of the coefficient of linear regression revealed that the prediction by CERES-Rice were accurate for the DMC or LAB treatments.

### 3.3 Generated climate data

SIMMETEO was used to generate daily weather data for a 90-year dataset. The average rainfall was  $1,398 \pm 288$  mm with a maximum of 1,965 mm and a minimum of 711 mm. Six years were very dry as total rainfall did not reach 900 mm. The rainfall distribution over the 90-year period is represented in Fig. 1.

### 3.4 Performances of the tillage systems under three climate changes

DSSAT-CSM was used to simulate the following crop rotation: rice/fallow/beans/oats for the 90 years. Automatic planting dates were used for rice, beans, and oats according to soil moisture and temperature thresholds.

### 3.4.1 Phenology

Simulated phenology varied depending on the climatic conditions. Emergence date was not modified by the climate changes (Table 2) as the automatic planting operation was usually triggered by the soil moisture content rather than by the temperature threshold. Whereas anthesis and maturity dates differed depending on the climatic change concerned. The higher the temperature, the faster the plants developed. Using climate data from the optimistic and pessimistic scenarios, anthesis occurred respectively 4 and 12 days earlier than in the control (Table 3). The same trend was observed for the maturity date, which occurred respectively 6 and 18 days earlier than in the control. Unsurprisingly, the other treatments had little effect on the phenology (Tables 2 and 3).

### 3.4.2 Dry matter and yields

Variance analysis revealed no interaction between treatments (data not shown). Thus, differences in yields between the tillage systems could not be detected whatever the fertilization or climatic change used. The DMC treatment did not increase yields compared to the LAB treatment. Moreover, DMC did not increase water use efficiency (Table 3) or N uptake by the crop. These results are in accordance with those obtained by Dusserre et al. (2010), who concluded that rice crops cultivated with DMC in the same region produced similar or lower yields. These authors hypothesized that to significantly increase the soil properties, DMC requires high levels of dry matter production and that the low temperatures that prevail in the region are a major obstacle to achieving this goal. It could be argued that the mulch-based cropping system would become appropriate with the rise in temperature expected under the pessimistic scenario. Unfortunately, our results did not confirm this hypothesis; there was no

comparative improvement in productivity with the mulch-based system and under the “high temperature” scenario.

Bean yields averaged  $3,631 \pm 867$  kg/ha of standard error (SE). Yield was significantly and the tillage treatments. The optimistic scenario produced the highest yield:  $250 \text{ kg ha}^{-1}$  more than the control, while the pessimistic scenario produced  $300 \text{ kg ha}^{-1}$  less than the control.

Rice yields averaged  $5,478 \pm 1,672$  kg  $\text{ha}^{-1}$  of SE (Table 3). The model simulated significantly higher yields under the pessimistic scenario:  $+576 \text{ kg ha}^{-1}$  compared to the control. This reflects that the increase in temperature with the pessimistic scenario accelerated flowering onset and the physiological maturity of the grains so that the demand for water and nutrients from the crop was more adequately fitted with their availability from the soil, i.e., the most favorable period for crop growth is January/February. This is reflected in Table 2, with changes in phenology and where crop weight at maturity is not significantly affected by climate change when harvest weight at maturity is. Figure 3 shows simulated rice grain yields over the 90 years. This figure illustrates two results: (1) firstly, it shows that the variability of the rice yields for the control treatment and the optimistic scenario is very high (from 2,000 to 7,000  $\text{kg ha}^{-1}$ ) whereas it is lower for the pessimistic scenario (from 5,000 to 7,500) and (2) secondly, it shows that the difference in rice yield simulated with the pessimistic scenario and the other treatments is increasing over the years.

The response of rice yields to nitrogen fertilization was very high:  $1,500 \text{ kg ha}^{-1}$  of rice grain for  $45 \text{ kg ha}^{-1}$  of nitrogen. This reflects the fact that nitrogen is a major constraint in this kind of soil. The quantity of nitrogen in the soil is sufficient (Rakotoarisoa et al. 2010) but its availability is low due to the low anionic exchange capacity of the soil (Chapuis-Lardy et al. 2009), and leaching (Rakotoarisoa et al. 2010).

**Table 2** ANOVA results on the emergence date (EDAT, jj), anthesis date (ADAT, jj), maturity date (MDAT, jj), top weight (CWAM,  $\text{kg ha}^{-1}$ ), yield (HWAM,  $\text{kg ha}^{-1}$ ), yield/rain productivity (Yd–Rain,  $\text{kg ha}^{-1} \text{ mm}^{-1}$ ), yield/transpiration productivity (Yd–trans,  $\text{kg ha}^{-1} \text{ mm}^{-1}$ ), and nitrogen uptake (NUCM,  $\text{kg ha}^{-1}$ )

	ANOVA			
	Model Pr>F	Tillage	Fertilization	Climate changes
<b>Phenology</b>				
EDAT	0.98	0.98	0.92	0.83
ADAT	0.002	0.86	0.66	<0.001
MDATE	<0.001	0.96	0.47	<0.001
<b>Productivity</b>				
CWAM	<0.001	0.21	0.0001	0.96
HWAM	<0.001	0.94	0.343	0.002
Yd–rain	<0.001	0.92	<0.001	0.001
Yd–trans	<0.001	0.47	<0.001	0.004
NUCM	<0.001	0.18	<0.001	0.051

jj Julian date

**Table 3** Means and Student's Newman-Keuls test for emergence date (EDAT, jj), anthesis date (ADAT, jj), maturity date (MDAT, jj), top weight (CWAM, kg ha<sup>-1</sup>), yield (HWAM, kg ha<sup>-1</sup>), yield/rain productivity (Yd-Rain, kg ha<sup>-1</sup> mm<sup>-1</sup>), yield/transpiration productivity(Yd-trans, kg ha<sup>-1</sup> mm<sup>-1</sup>), nitrogen uptake (NUCM, kg ha<sup>-1</sup>), soil organic carbon (soil OC, t ha<sup>-1</sup>), and soil organic nitrogen (soil ON, t ha<sup>-1</sup>) in 2020, 2050, and 2080

	Mean	Tillage		Fertilization		Climate changes		
		DMC/LAB		Low/high		Control/optimistic/pessimistic		
<b>Phenology</b>								
EDAT	308	308	308	308	308	308	307	307
ADAT	20	20	20	21	19	25 a	21 a	13 b
MDATE	53	53	53	52	54	61 c	55 b	43 c
<b>Productivity</b>								
CWAM	14,100	13,863	14,332	12,088 b	16,106 a	14,331	13,650	14,310
HWAM	5,478	5,381	5,567	4,720 b	6,229 a	5,248 b	5,351 b	5,824 a
Yd-rain	8.1	8.1	8.1	7.0 b	9.2 a	7.3 b	7.4 b	9.6 a
Yd-transp	11.7	11.6	11.8	10.9	12.5	11.3 b	11.6 b	12.3 a
NUCM	146	143	148	122 b	169 a	150	140	148
<b>Soil OC</b>								
2020	117.0	117.0	117.0	115.5	118.5	116.2	117.4	117.3
2050	117.3	117.1	117.4	115.0	119.4	116.8	118.1	116.7
2080	108.3	108.3	108.3	106.4	110.1	111.7	105.7	107.4
<b>Soil ON</b>								
2020	14.9	14.9	14.9	14.8	15.0	14.9	15.0	14.9
2050	14.7	14.7	14.8	14.5	14.9	14.7	14.8	14.6
2080	13.7	13.6	13.7	13.6	13.9	14.0	13.6	13.6

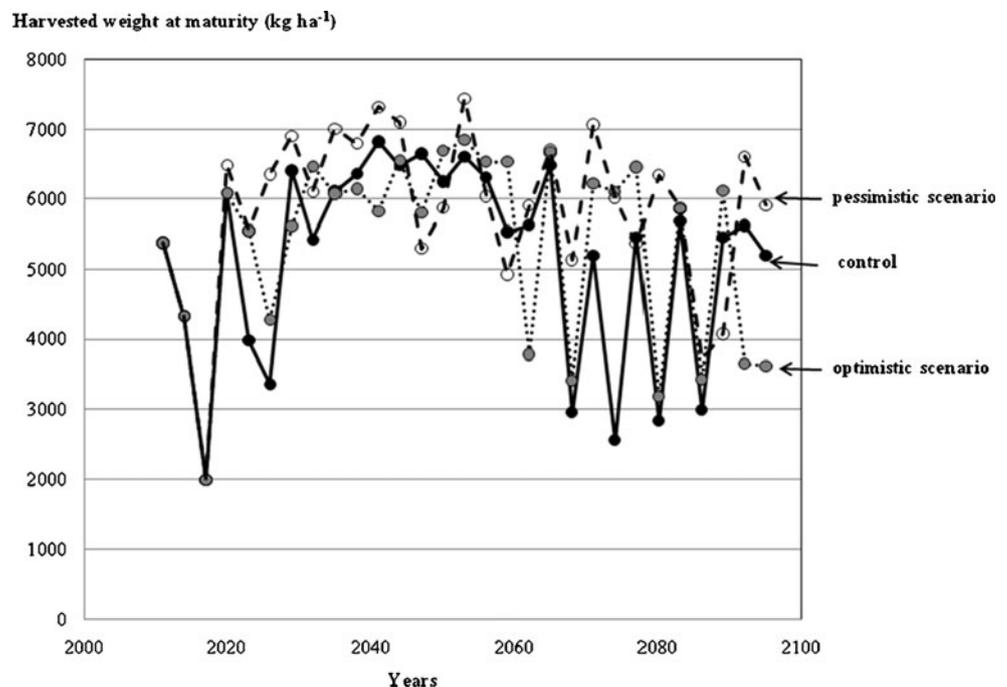
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### 3.4.3 Productivity

Yield-rain productivity averaged 8.1 kg ha<sup>-1</sup> mm<sup>-1</sup> with no effect of the tillage treatment, but a significant effect of

fertilization and climate treatments (Table 3). The rain productivity of the high fertilization treatment was 3.2 kg ha<sup>-1</sup> mm<sup>-1</sup> higher than with the low fertilization treatment. Rain productivity under the pessimistic scenario

**Fig. 3** Simulations of the grain yields of rice from 2011 to 2095 under three climatic conditions. *Control* no climate change, *optimistic scenario* a gradual increase in CO<sub>2</sub> up to 750 ppm and a rise in temperature of 0.15°C per decade, *pessimistic scenario* a gradual increase in CO<sub>2</sub>, a rise in temperature of 0.5°C per decade, and a reduction in rainfall (-0.2 mm day<sup>-1</sup>) from December to February



was 2.3 kg ha<sup>-1</sup> mm<sup>-1</sup> higher than the control. The same trend was observed in yield–transpiration efficiency, but to a lesser extent, as the difference between the pessimistic scenario and control was only 1 kg ha<sup>-1</sup> mm<sup>-1</sup> and the difference between high and low fertilization only 1.6 kg ha<sup>-1</sup> mm<sup>-1</sup>. Half the increase in rain productivity was due to the transpiration efficiency. For the other half, we assume that water uptake was increased through the increase in water availability. This was probably due to a combination of root growth stimulation and the reduction in evaporation due to early closure of the canopy.

Nitrogen fertilization increased both rain productivity and transpiration efficiency. This might be due to an increase in root growth and photosynthesis.

### 3.4.4 Long-term dynamics in soil organic properties

The simulated soil organic carbon and nitrogen contents over the century are summarized in Table 3. It shows a decline in both variables over the time, with a sharp decline at the end of the century. Tillage treatments did not modify the trends, whereas the fertilization treatments did. The higher biomass produced and the larger amount of nitrogen applied with the high fertilization treatment had a cumulative effect over time and reduced the decline in carbon and nitrogen.

The simulations also showed that the climatic changes will accelerate carbon and nitrogen depletion in the soil. This result probably explains why the crop weight at maturity is not improved in the pessimistic scenario when the harvest yield is (Table 3).

## 4 Conclusion

We conducted a 6-year experiment in the Malagasy highlands and used our results to calibrate a crop model to assess the productivity of upland rainfed rice under future climate scenarios. Our results showed that the direct effect of climate changes could be positive for rice productivity in the highlands, especially under the most pessimistic scenario.

Environmental modifications caused by climate changes did not increase the comparative interest of no-tillage systems. Its productivity is still expected to be lower than with conventional tillage. However, other no-tillage systems might be more appropriate, especially those that increase root exploration and the nitrogen availability for rice crops.

The magnitude of the impacts of climate changes could be biased depending on the climate change uncertainty, the level of management, and the crop model. Aggarwal and Mall (2002) found that it could range from 1% to 33%. Our results are optimistic for food

security in Madagascar but they are based on average yields and mean changes in climatic parameters. They should thus be interpreted with caution in directing regional or national food policies.

Under climate changes, rice yields are expected to undergo a general decline in Asia (Matthews et al. 1995). This prediction reflects the fact that most rice crops are grown in south Asia at the upper limit of this crop's temperature tolerance. The reverse is the case in the Malagasy highlands where rice is grown at the lower limit of its temperature tolerance. Our study showed that the rice yield would increase under the “pessimistic scenario,” which is an optimistic prediction for Madagascar. The same results were obtained in Japan where climate changes are expected to increase yields in the northern parts of the country and to decrease yields in the central and southern parts (Matthews et al. 1997).

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