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Combined impacts of climate and nutrient fertilization on yields of pearl millet in Niger

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ABSTRACT

Effects of climate variability and change on yields of pearl millet have frequently been evaluated but yield responses to combined changes in crop management and climate are not well understood. The objectives of this study were to determine the combined effects of nutrient fertilization management and climatic variability on yield of pearl millet in the Republic of Niger. Considered fertilization treatments refer to (i) no fertilization and the use of (ii) crop residues, (iii) mineral fertilizer and (iv) a combination of both. A crop simulation model (DSSAT 4.5) was evaluated by using data from field experiments reported in the literature and applied to estimate pearl millet yields for two historical periods and under projected climate change. Combination of crop residues and mineral fertilizer resulted in higher pearl millet yields compared to sole application of crop residues or fertilizer. Pearl millet yields showed a strong response to mean temperature under all fertilization practices except the combined treatment in which yields showed higher correlation to precipitation. The crop model reproduced reported yields well including the detected sensitivity of crop yields to mean temperature, but underestimated the response of yields to precipitation for the treatments in which crop residues were applied. The crop model simulated yield declines due to projected climate change by −11 to −62% depending on the scenario and time period. Future crop yields in the combined crop residues + fertilizer treatment were still larger than crop yields in the control treatment with baseline climate, underlining the importance of crop management for climate change adaptation. We conclude that nutrient fertilization and other crop yield limiting factors need to be considered when analyzing and assessing the impact of climate variability and change on crop yields.

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1. Introduction

Crop production is vulnerable to climate change because meteorological variables determine resource availability (solar radiation, water) and control basic processes involved in crop growth and development (Meza and Silva, 2009). Changes in temperature and precipitation associated with continued emissions of greenhouse gases will cause changes in land suitability and crop yields (Schmidhuber and Tubiello, 2007). Lobell and Field (2007), for example, found a distinct negative response of global wheat, maize and barley yields to increased temperatures during the period 1981–2002. Interactions between different climate variables were simulated to decrease crop yields when humidity and precipitation decreased or when temperature increased and precipitation decreased under climate change in the central parts of the USA (Brown and Rosenberg, 1997).

The economy and food security of the rural communities in the semi-arid regions of Niger are strongly dependent on rainfed agriculture (Marteau et al., 2011). Pearl millet (*Pennisetum glaucum* [L.]) is one of the most important crops growing on more than 65% (7.5 million ha^{-1}) of the cultivated land of Niger (Mariac et al., 2006). Different reports showed significant impacts of climate change on crop production in West Africa, which is according to the Global Hunger Index, one of the regions with the most severe hunger in the world (Grebmer et al., 2008). Ben Mohamed et al. (2002) and Van Duivenbooden et al. (2002) predicted that 10% increase in average temperature may cause a 13% decrease in millet production by using an empirical method for Niger. Furthermore, Tingem and Rivington (2009) estimated 14 and 39% decrease in maize and sorghum yield under SRES-A2 emission scenario in

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Cameron. In general, 11% decrease in crop production under climate change was expected for the whole of West Africa (Roudier et al., 2011). Most climate change assessment studies did not account for differences in crop management and little is known on the interaction between climate and crop nutrition. Poor soil fertility management, high evapotranspiration demand and the low native soil fertility limit pearl millet production in Niger (Bationo et al., 1993). Changes in climate may cause larger (or smaller) losses of nitrogen through leaching and gaseous losses or changes in the demand for fertilizer, e.g. by changes in temperature and precipitation amount and pattern (Olesen and Bindi, 2002; Porter et al., 1995). Sivakumar and Salaam (1999) showed that the effectiveness of fertilizer application in this region depends on midseason precipitation. Average or above average midseason precipitation and high application rates of Nitrogen fertilizer resulted in highest yields of pearl millet while lower precipitation eliminated the advantage of nitrogen application. However, this study was a short term experiment (4 years) and only considered mineral fertilizer application as fertilization practice.

The main objectives of this study were therefore to investigate whether different nutrient fertilization strategies modify the sensitivity of pearl millet yields to temperature and precipitation and to which extend this affects simulations of climate change impacts on millet yield. To achieve this, an analysis of published data from different field experiments was combined with a crop model application. The widely used crop model DSSAT 4.5 was first evaluated to reproduce yield sensitivities to climate variables detected from the observations and then applied to investigate how crop yields would be affected in different fertilization treatments under observed historic and predicted future climate.

2. Materials and methods

2.1. Study area and data

2.1.1. Site description

This study focused on Niamey region which is located in the Sahelian bioclimatic zone, a wide semi-arid belt immediately south of the Sahara desert. It is one of the most important agricultural centers of Niger and has a population of more than 1.5 million inhabitants (Bationo and Ntare, 2000). Agriculture is the main source of income for 95% of the population and rainfed pearl millet represents the major food crop (Sivakumar, 1992). Mean monthly temperature of this region in the period 1940–2005 was highest in May (34 °C) and lowest in January (24 °C), while mean monthly precipitation sum was highest in September (178 mm) and lowest in December (0 mm). Mean annual precipitation was 555 mm and varied between 293 mm (1981) and 980 mm (1942). The soil at this region is classified as sandy siliceous with 94% sand and 3% clay content in the top soil (Bationo et al., 1998). More than 60% of pearl millet cultivated lands of Niger were classified as Arenosols soils (Graef, 1999). Furthermore, Marteau et al. (2011) reported soil characteristics of 10 pearl millet cultivated centers (including our study location) indicating that they had similar field capacity and wilting points.

2.1.2. Crop yield and crop management

Data collected from three short and long term pearl millet yield experiments were obtained from the literature and used in this study for detection of climate and fertilization management interactions (long term field experiment), parameterization (short term field experiment 1) and testing (short term field experiment 2) of the crop model. The long term experiment was undertaken in the period 1983–1995 to test the impact of the application of crop residues (CR), the application of mineral fertilizer (FR), and combined crop residues and mineral fertilizer application (CR + FR).

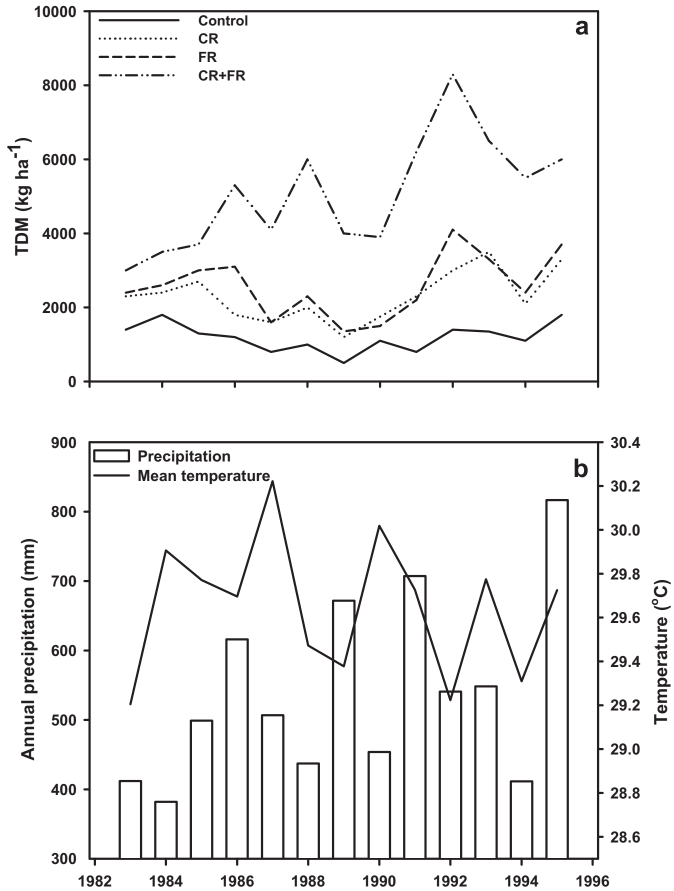

Fig. 1. Pearl millet total dry matter yield (TDM) for the treatments without fertilizer application (control), application of crop residue (CR), application of synthetic fertilizer (FR), and combined application of crop residue and synthetic fertilizer (CR + FR) (a), and climatic variables (b) observed in the long term experiment between 1983 and 1995 (yield data were obtained from Bationo et al., 1998).

Fertilizer application rate was 15 kg P ha^{-1} year^{-1} applied as single superphosphate and 30 kg N ha^{-1} year^{-1} applied as calcium ammonium nitrate (Bationo et al., 1998) while the biomass (except grains) was returned to the soil each year in the treatments with residues application (Bationo et al., 1993). Crop yields recorded in this experiment are shown in Fig. 1.

Data collected in short term experiment 1 and reported in Sivakumar and Salaam (1999) were used for crop model parameterization (genotype coefficients estimation) of the CIVT pearl millet cultivar. The field experiment was conducted in 1984 at the ICRISAT Sahelian center, Sadore, Niger. The study evaluated water use efficiency, growth and yield responses of pearl millet fertilized with 30 kg P ha^{-1} and 45 kg N ha^{-1} or grown without fertilizer application.

Short term experiment 2 was undertaken at ICRISAT Sahelian center, Sadore, Niger in period 1986–1987 to test the impact of an early onset of precipitation (imposed with supplemental irrigation) on crop yield of the CIVT cultivar compared to a natural onset of precipitations (Sivakumar, 1990). Pearl millet yields from this experiment were obtained from (Sivakumar, 1990) and used for model testing.

2.1.3. Climate data

Daily time series of maximum, minimum and mean temperature (°C), precipitation sum (mm day^{-1}) and global radiation (MJ m^{-2} day^{-1}) for the period 1940–2005 were measured by an automated weather station and provided by Niger meteorological

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