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CERES-Maize and CERES-Sorghum for modeling growth, nitrogen and phosphorus uptake, and soil moisture dynamics in the dry savanna of West Africa

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ABSTRACT

Sustainable production practices are needed to enhance water and nutrient use efficiencies in the cropping systems of West Africa, especially in face of predicted climate change for the region. Crop simulation models may assist in exploring alternative management systems for optimizing water and nutrient use efficiencies, increasing crop production, and easing food insecurity. The twofold objectives were: (i) to access the ability of the CERES-Maize and CERES-Sorghum models for predicting yields, nitrogen (N) and phosphorus (P) uptake, and in-season soil water and N dynamics during maize and sorghum growth; (ii) to use the models to assess the effects of different nutrient management strategies on soil C and N, and crop water and N use efficiencies considering 30 years of historical weather variability in the dry savanna agro-ecological zone of northern Benin, West Africa. Both models were calibrated with data from a researcher-managed field trial (2014) and validated with independent findings (2015). The models were next evaluated with datasets collected from researcher- and farmer-managed field trials conducted under rainfed and supplementary irrigation conditions (2014–2015). The parameterized CERES-Maize and CERES-Sorghum models accurately predicted biomass accumulation with a normalized root mean square error (nRMSE) of 18% and 17%, respectively, and an index of agreement (d) of 0.98 for both crops in non-nutrient- and non-water-stressed conditions. Under rainfed and rainfed with supplementary irrigation conditions, both with and without mineral fertilizer application, CERES-Maize predicted biomass accumulation with nRMSE (d) of 10–22% (0.96–0.99), while CERES-Sorghum reached accuracies of 13–29% (0.97–0.99). Grain yield was simulated with nRMSE (d) of 19% (0.93) and 15% (0.89) by CERES-Maize, and 16% (0.91) and 15% (0.80) by CERES-Sorghum in researcher-managed and farmer-managed fields, respectively. CERES-Maize predicted reasonably well nutrient uptake with nRMSE (d) ranging from 14 to 40% (0.89–98) for N and between 24 and 49% (0.90–0.98) for P. Similarly, CERES-Sorghum simulated N uptake with nRMSE of 17–49% and d-values of 0.87–0.98, and P uptake with nRMSE of 42–62% and d-values of 0.82–0.93. Values of nRMSE (d) between predicted and measured in-season soil water and N dynamics were 6–13% (0.61–0.87) and 46–58% (0.61–0.76) with CERES-Maize, and 14–20% (0.75–0.89) and 35–56% (0.62–0.82) with CERES-Sorghum, respectively. The models simulated improved soil organic C and inorganic N, water and N use efficiencies, and grain yields with the integrated soil-crop management system compared to un-amended soil and high mineral fertilizer use options under 30 years of weather variability. Both models are thus appropriate tools not only to explore potential impacts of predicted climate change on soil water and nutrient use efficiencies, but also to frame more sustainable intensification measures in the maize- and sorghum-based production systems of West Africa.

1. Introduction

Declining agricultural productivity, demographic growth, urbanization, and changing consumption habits are major drivers of the increase in the demand for food and feed in West Africa (Garrity et al., 2010; Schlecht et al., 2007; Wheeler and von Braun, 2013). The trends for more demand are further challenged by dwindling resources as manifested by widespread soil fertility depletion and evidenced by low

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soil organic matter (Schlecht et al., 2007) and chronic N and P deficiencies (Bationo et al., 2012). Furthermore, consent exists that the predicted changes in climate and agricultural land use will adversely alter nutrient dynamics (Whitehead and Crossman, 2012), and likely exacerbate the impacts of soil fertility depletion on crop productivity and resource use efficiency (Wu and Ma, 2015). This, in turn, threatens the diversity of the prevailing cropping systems (Callo-Concha et al., 2013), which usually are dominated by staple crops. Therefore, unless action is taken, agricultural land degradation and increasing climate variability will jeopardize food security in West Africa (Wheeler and von Braun, 2013), particularly the availability of maize and sorghum, which are major local staple food crops (Garrity et al., 2010). Under the current conditions of food insecurity and limited access to and affordability of production factors (Wheeler and von Braun, 2013), there is an urgent need to improve resource use efficiencies and yields in smallholder production systems (Wu and Ma, 2015). Hence, sustainable intensification practices are required in the region (Drechsel et al., 2015; Vanlauwe et al., 2014) to ensure production of sufficient, affordable, and nutritious food without compromising the environment.

Field experimentation has been pivotal in assessing the effects of single or multiple factors on crop productivity. However, given the growing costs of conducting multi-level, multifactorial, and long-term field experiments to respond to the existing complexities in soil-plant-climate interactions, complementary approaches are needed. Process-based models are recognized to complement empirical data collection to support decision-making (Tsuji et al., 2013) concerning not only crop responses to soil fertility management, but also the framing of alternative measures to increase the resilience of production systems. While a wide array of simulation models have been assessed for their use in West Africa (Akinseye et al., 2017; Webber et al., 2014), the Decision Support System for Agrotechnology Transfer (DSSAT) – Cropping System Model (CSM) (Jones et al., 2003) appears promising to simulate soil-plant-climate interactions in this region. Reportedly, CSM-CERES-Maize and CERES-Sorghum of the DSSAT can simulate growth, development, and yield in response to weather conditions and soil/crop management (Hoogenboom et al., 2015). They are also recognized to simulate soil water (Ritchie, 1998) and N-balance (Godwin and Singh, 1998) in cropping systems and climate change impacts on crop production (White et al., 2011). Both CERES-Maize and CERES-Sorghum have been extensively tested in terms of crop growth and yield predictions and N fertilizer management in India (Liu et al., 2013; Yang et al., 2011), Togo (Dzotsi et al., 2003), Ghana (Fosu et al., 2012; McCarthy et al., 2012), Mali (Akinseye et al., 2017), Nigeria (Adnan et al., 2017; Jagtap et al., 1993; Jibrin et al., 2012), and Benin (Igue et al., 2013). However, these models have hardly been screened in terms of soil water and nutrient dynamics under typical environment of the dry savanna regions of West Africa. While it has been postulated that seasonal soil moisture dynamics potentially affect the soil supply of N and P (Bationo et al., 2012) and crop nutrient uptake (Buerkert and Hiernaux, 1998), neither processes have been modeled by CSM-CERES and therefore do not yet support the framing of better soil-crop and water management options in this region.

Recent improvements enable CERES-Maize and CERES-Sorghum to respond to conditions of low N and P (Dzotsi et al., 2010; Gijsman et al., 2002; Porter et al., 2009), which are typical for the production environment in the dry savanna zone of West Africa, including northern Benin. However, before exploiting the potential of these models to predict the consequences of climate change on crop growth, development, soil water dynamics and nutrient balances, they must be parameterized and evaluated for these agro-ecological conditions and must prove to be sufficiently robust to respond to these typically N- and P-poor environments. The twofold objectives were: (i) to access the ability of the CERES-Maize and CERES-Sorghum models for predicting yields, nitrogen (N) and phosphorus (P) uptake, and in-season soil water and N dynamics during maize and sorghum growth; (ii) to use the models to assess the effects of different nutrient management strategies on soil C and N, and crops water and N use efficiencies considering 30 years of historical weather variability in the dry savanna agro-ecological zone of northern Benin, West Africa.

2. Materials and methods

2.1. Description of the CERES-Maize and CERES-Sorghum models

CSM-CERES-Maize and CERES-Sorghum within the DSSAT Version 4.6 (Hoogenboom et al., 2015) are process-level, comprehensive models to simulate crop growth, development, and final grain yield of maize and sorghum. The models simulate growth and development using a daily time-step routine from sowing to maturity or a specified harvest time based on physiological processes that describe crop responses to soil and weather conditions. Phenological development and growth are specified by cultivar-specific genetic coefficients depending on the photoperiod, thermal time, temperature response, and dry matter partitioning. Both models account for temperature effects on crop growth and grain filling rate based on cardinal temperatures, assuming trapezoidal responses and an optimum temperature of 34 °C (Kumudini et al., 2014; White et al., 2015). Potential dry matter production is assumed to be proportional to the photosynthetically active solar radiation absorbed by a crop canopy. The actual dry matter production on a given day is constrained by suboptimal air temperature, soil water deficits, or N and P deficit factors for crops. The dry matter simulated is partitioned into different parts of the plant on the basis of temperature and phenological stage of the crop (Hoogenboom et al., 2010; Ritchie et al., 1998). Soil water, N, P, and organic C dynamics and their interactions with crop management are determined in subroutines that are shared by all crops in CSM. More detailed descriptions of the soil water, N, and C balance dynamics are found in Ritchie (1998) and Godwin and Singh (1998), but elements key to the present study are briefly described hereafter.

The soil-water balance component simulates the daily water balance processes, i.e. infiltration (rainfall and irrigation), surface runoff, drainage, evaporation from the soil surface, and water extraction by the plant. The downward flow of soil water to lower soil layers occurs according to a cascading approach based on the water content between saturation (SAT) and drained upper limit (field capacity, DUL); this flow is a determinant in computing the share of nitrate leaching (Ritchie, 1998). The CERES-N balance routine for upland cropping systems simulates the turnover of soil organic matter and the decay of crop residues with the associated mineralization and/or immobilization of N, the major N loss processes (nitrification of ammonium and associated denitrification), and the contribution to the N balance made by mineralization. The model neither simulates losses by ammonium volatilization or ammonium exchange equilibria nor nitrogen dioxide (N_2O) and dinitrogen (N_2) emissions (Bowen and Baethgen, 1998; Gijsman et al., 2002; Godwin and Singh, 1998). Recent adaptation of CENTURY-based soil organic matter-residues module for DSSAT-CSM allows better understanding of soil organic nutrient processes (Gijsman et al., 2002; Parton et al., 1988; Porter et al., 2009).

The routine simulates plant N uptake and distribution within crops, the remobilization during grain filling, and the effects of N deficiency on crop growth processes. The N-deficit demand is defined as the difference between a critical N concentration and an actual N concentration in the plant. The potential N uptake is the product of soil inorganic N concentrations, root length density, maximum N uptake per unit root length, and a soil water factor. The actual N uptake is determined as the lesser of either potential crop N demand or potential N uptake. The NFACT submodel calculates N-deficit factors in maize and sorghum.

The soil-plant P-submodule integrates inorganic P pools (labile, active, and stable) and organic P pools (active and stable) with plant P uptake (Dzotsi et al., 2010). The P-submodule computes daily P transformation between the pools in the roots and non-roots zones of the soil. The P uptake is constrained by the minimum of plant demand and

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